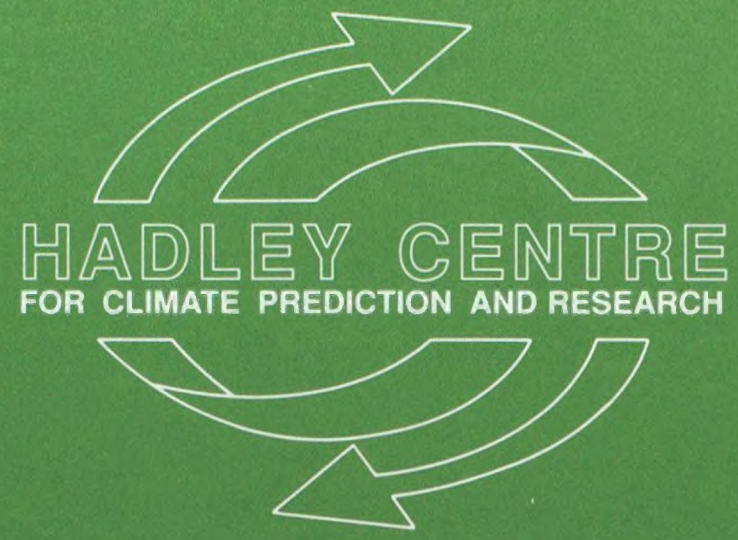

Global data required for monitoring climate change

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CRTN 46

April 1994

CLIMATE
RESEARCH
TECHNICAL
NOTE

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CLIMATE RESEARCH TECHNICAL NOTE NO. 46

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Adapted from an Invited Lecture given by C K Folland
at the IAMAP-IAHS Joint Symposium on Global Monitoring
and Advanced Observing Systems, Yokohama, Japan, July 1993

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ABSTRACT

A review is given of the chief data needs for monitoring global climate change on multidecadal and longer time scales, and for some aspects of its detection. We focus on data that can be expected to deliver results over the next one to two decades that will be significant for policy-makers. So some kinds of satellite data planned for the future are not covered. Monitoring of the shorter time scales commonly referred to as 'climate variability' is included, as the monitoring of change requires that "noise" due to variability be first accounted for and understood. The various needs are illustrated from recent climate change research.

Monitoring of climate change requires above all the creation of long homogeneous data sets, several decades to a century or more in length. Such data sets often require the blending of more than one kind of data and the extensive adjustment of data for time-varying biases. Examples of the latter are land-based rainfall and sea surface temperature. Large data gaps often exist in time and space and can give rise to considerable uncertainties in estimates of global and regional climate change. There are prospects for reducing these uncertainties by incorporating historic data that so far have not been utilised into existing analyses. A promising example of one such activity is given.

A straightforward way of dividing the primary data types needed for monitoring is into the basic methods of obtaining them, i.e. sub-surface ocean data, surface-based data (including radiosondes and ocean surface measurements), space-based data and, soon, three dimensional reanalysed numerical model data for the atmosphere. We highlight important needs under these categories by discussing some conclusions of the 1990 and 1992 Scientific Assessments of the Intergovernmental Panel on Climate Change, and the difficulties that were encountered.

An increasingly important research activity that will allow more complete data sets to be created is the development of methods of blending different data sources, such as space-based and surface-based data and sometimes numerical model data, into homogeneous sets. Key examples are sea surface temperature (SST) where work has started using in situ and space-based data and may use ocean model-based data; upper air temperature using radiosonde and microwave sounding unit data; and rainfall, where a combination of satellite data and ground-based data, and, soon, numerical model analyses, is emerging as a new possibility even for the recent past.

1. INTRODUCTION

The Second World Climate Conference, held in 1990, highlighted the need for adequate data for monitoring, analysis and understanding of the global climate system. Specifically, the Scientific and Technical part of the conference report stressed the following:

- Present observational systems for monitoring the atmosphere, cryosphere, land surface and oceans are inadequate for understanding and predicting climate change as they are not specifically designed for climate;

- There is a need to create a Global Climate Observing System (GCOS) which is designed specifically to meet the above needs and routinely measures all major elements of the global climate system to an appropriate accuracy;

- To minimize costs and lead-times, GCOS must build on existing and planned observing systems and research programmes;

- The development and implementation of GCOS must be pursued with urgency.

Subsequently, plans for GCOS have been formulated (ICSU/UNEP/UNESCO/WMO, 1993). In this paper we complement the approach followed in these GCOS plans. We do not list data requirements as this has already been done in the GCOS plans and by Carson (1991) and Parker (1993b). Rather, we use the underlying principles described in the GCOS plans as a framework for examining the characteristics and shortcomings of some key data-bases from the standpoint of monitoring climate and detection of climate changes.

The key aim of the GCOS plans is to ensure the development of an observation system dedicated to, and designed specifically for, monitoring climate, detecting climate change, and predicting climate variations and changes. This is in contrast to most existing observing networks, which are dedicated to and designed for the support of operational short-term weather prediction or the estimation of the mean climate near the ground rather than its subtle changes and the causes of change. Activities for which GCOS is crucial include seasonal and interannual climate prediction, insights from which promise to help considerably with understanding climate change (Folland, 1993), the timely detection of human-induced climate changes, and, through the verification of climate prediction models, the reduction of the major uncertainties in longer-term climate prediction (ICSU/UNEP/UNESCO/WMO, 1993). Recently, all these scientific activities have been brought together under the umbrella of the WRCP CLIVAR Program (WCRP, 1992), formally agreed early in 1993. There are also important applications to economic development and in the monitoring of ecosystems' responses to climate variations. All these activities currently suffer from the use of an observing system designed, and funded, for another purpose.

To monitor climate and detect its changes, long, complete, homogeneous data sets are required. The types of data and the accuracies needed at specified geographical and temporal resolutions are surveyed by Carson (1991) and Parker (1993b). The requirements for homogeneity and completeness are much more stringent than for operational weather prediction. We illustrate these needs in Section 2.

Detection of climate change includes its attribution to, for example, human-induced pollution. Here a detailed knowledge of the modes of natural variability, and an understanding of their mechanisms, is essential, along with an ability to use the observations to search for, and assess the fingerprints of, human-induced climate changes indicated by climate models. To support these requirements, we need ground-based and satellite data, blended data formed from both of these, subsurface ocean data, and model-assimilated data including calculated quantities such as vorticity, divergence and diabatic heating. Subsequent sections therefore

illustrate shortcomings and potential improvements in the observing system under these categories. Some elements of the needed observing system have recently been developed for the Tropical Ocean-Global Atmosphere (TOGA) programme and for the World Ocean Circulation Experiment (WOCE). Success of the replacement programme on climate variability (CLIVAR) depends on a continuation and expansion of these observing networks under the aegis of GCOS.

2. DEVELOPMENT AND NEED FOR LONG, HOMOGENEOUS DATA SETS AND EXAMPLES

2.1 Data length with examples from surface temperature

The length of record required for the detection and attribution of climate changes is determined by the time-scales of natural climate variability. *Any variation is likely to be misinterpreted as a trend by a record shorter than the variation.* Figure 1 compares the length of various existing major data bases with the timescales of climatic variation as represented by the global annual average combined land and SST anomaly record for 1861-1993 (Jones, 1988; Bottomley et al., 1990; Jones and Briffa, 1992; Folland and Parker, 1994). The very short satellite-based SST records and Microwave Sounding Unit (MSU) tropospheric and stratospheric temperature records commenced after the warming of the mid to late 1970s, and therefore any trends which may be evident in these satellite-based data cannot be interpreted without the support of the longer data bases. The radiosonde record, while longer, is too short to detect the secondary maximum of global mean temperature that occurred around 1940. Only the records of surface temperature over land and sea, precipitation over land, and mean-sea-level pressure are long enough to assess the multidecadal-to-century time-scale natural variations which can be expected to continue and to be superimposed on any future greenhouse-gas or aerosol-induced climate changes regionally or even globally. Even these records, to be correctly interpreted, require a considerably longer-term perspective which it may never be possible to provide in full but can be obtained in some measure from earlier instrumental records, palaeoclimatic data and written accounts. These considerations underlie the discussions of palaeoclimatology in the IPCC Reports (Folland et al., 1990, 1992). However palaeoclimatic data need to make a much bigger impact in future, particularly for the period 1000 years ago to 100 years ago.

The apparent completeness of the 133-year time-series in Figure 1 conceals major time-varying shortcomings in geographical coverage. Many corresponding time-series for much smaller areas would be much shorter, or broken. Over land, for example, few Antarctic data exist before 1958, and operational receipt of African and South American monthly climate data has been declining in recent years (Figure 2): such a trend needs urgently to be reversed. Over the oceans, there were vast data voids in the 19th century and early twentieth century, during and around the two world wars, and in the Southern Ocean until the era of satellite data (Figure 3). However, Figure 3 also suggests a partial remedy: digitization of several major, hitherto untapped, historic data bases. Plans have been made to digitize Maury's collection (see also Maury, 1858) of about a million observations made from commercial ships worldwide mainly in the mid-19th century (J.Elms, pers. comm. 1994): each observation can, and usually does, include air and water surface temperature, mean-sea-level pressure, and wind. A manuscript Norwegian collection contains about half a million observations mainly from the northern North Atlantic and adjacent seas between 1868 and 1900, though not all may be new observations: this is being digitized (S.Woodruff, pers. comm. 1993). Progress has been made on the digitization of about 3 million USA observations for the periods around and during the two world wars (Elms, 1992 and pers. comm. 1994). There are also 5 to 6 million undigitized Japanese observations made between 1891 and 1941 mainly in the northwestern Pacific (Komura and Uwai, 1992; S.Woodruff, pers.comm. 1993) where available data for most of that period are very sparse. When available, these enhancements will significantly fill in some of the data-sparse regions in Figure 3, and so improve

the historical perspective of present-day climate monitoring, especially for SST, marine air temperature and marine atmospheric circulation.

2.2 Problems of data homogeneity with examples from surface temperature

Homogeneity of data is vital for monitoring and understanding climate variations and changes. Historical developments in instrumentation, while being improvements from the viewpoint of precision or technological convenience, have often introduced inconsistencies into time-series of climate data. The record of SST is a good example. At the start of the record, wooden buckets were often used to collect sea water (Maury, 1858), but canvas buckets or other types which lose heat more readily before the temperature can be measured became the norm by the early 20th century (Folland and Parker, 1994). Around the second world war a rapid switch took place to predominantly engine-intake data, yielding a sudden, artificial warming in the raw data (Folland et al., 1984). Thereafter a changing mix of engine intakes, insulated buckets and hull-sensors have been in widespread use, giving smaller but not necessarily negligible biases, particularly in the engine intake data (Folland et al, 1993; Kent et al., 1993). Bottomley et al. (1990) outline a technique for adjusting the pre-second world war SSTs: a refined form of this technique is described fully by Folland and Parker (1994), who illustrate a set of seasonally, geographically and temporally varying corrections. Figure 4 shows that the overall corrections to hemispheric SST are only a little less than the magnitude of assessed global warming. Figure 4 also includes night marine air temperatures (NMAT) which are mostly measured in similar locations to SST, They have been independently corrected since the 1890s (Bottomley et al., 1990), so serve as a reference. Daytime data are avoided to avoid the marked biasing effects on air temperature of the solar heating of ships' decks (Bottomley et al., 1990). The improved agreement between corrected SST and NMAT indicates that corrections to these data sets are needed, and that the corrections made so far have improved our ability to assess the size of ocean surface temperature change over the last century. Some doubts remain about current SST data because engine intake samples of sea water used to measure the SST seem overall to be warmer than sea water collected by other current methods (Folland et, al, 1993, Kent et al, 1993). A progressive increase in the fraction of engine intake data suspected to have occurred since the 1950s may have caused a small artificial warming trend in SST since then. Thus the mix of methods by which in situ SST data are currently collected is not fully satisfactory for climate change studies.

Satellite-based SSTs have the virtue of more completely covering the oceans and Reynolds (1988) has homogenised these with in situ data since 1982 via a Laplacian blending technique. Here the satellite SSTs are adjusted to remove mean biases, and linear gradients in the biases, relative to concurrent ships' and buoys' SSTs, while retaining as far as possible the geographical patterns of temperature gradient in the satellite data. This process is necessary (Folland et al., 1993) and was particularly useful when aerosols from the April 1982 eruption of El Chichon in Mexico and the June 1991 eruption of Pinatubo in the Philippines introduced extensive and large negative biases into satellite SSTs. These biases were at least -1°C in much of the tropics in 1991, with lesser biases beyond (Reynolds (1993); see also section 3.3 below). However, even 'perfect' satellite SSTs, or much-improved data anticipated from the Along-Track Scanning Radiometer (ATSR) series (Saunders et al., 1993), differ intrinsically from conventional SSTs in measuring the ocean surface "skin" rather than bulk temperature, so do not provide data homogeneous with the latter. Genuine differences between these two temperatures can be substantial (Schluessel et al., 1990). Thus adjustments to satellite SST data will always be required for climate change studies. However, this is still not a completely satisfactory method if the mix of in situ data also has time-varying biases.

Techniques for producing globally-complete fields, such as optimum interpolation

(Gandin, 1963) have not so far treated biases explicitly (as opposed to random errors), so those must be removed first (Reynolds and Smith, 1994). The planned grid-point data-bases to be created by reanalysis of recent historical data using fixed numerical models (Bengtsson and Shukla, 1988) will inevitably still contain time-varying biases because some temporally heterogeneous data, for example from radiosondes, are expected to be supplied to the models. Different models may also introduce different biases, especially in data-sparse regions. Thus heteorogeneity can still be a problem in reanalyses even if model-related time-varying biases have been eliminated.

3. GENERIC TYPES OF MONITORING DATA

We discuss some shortcomings and promises of ground based data, including those from radiosondes; satellite-based data; blended ground-based and satellite-based data; subsurface ocean data; model-assimilated data; and model-calculated data. Alternative breakdowns are possible, e.g. division by quantities measuring forcing, feedbacks and passive responses. However, particular measurements, especially of radiative properties, may span all three of these categories. In addition, a 'passive responder' on one space and time-scale may constitute a feedback on a larger and longer space and time-scale. Thus SST may appear to respond rapidly and passively to local radiative or atmospheric forcing, but it will be part of a feedback chain involving evaporation and atmospheric water vapour and ultimately radiation and atmospheric circulation on a longer time scale and larger space scale. So a breakdown by generic types of data seems best. Our list is not intended to be exhaustive: ships' sea surface and marine air temperatures have already been discussed (section 2) and are therefore not included in section 3.1 below. We have concentrated attention on non-satellite data, and on those satellite data with most potential in the medium term to detect climate change, especially when blended with in situ data. Other data are discussed by ICSU/UNEP/UNESCO/WMO (1993).

3.1 Ground-based measurements

a) Maximum, minimum and mean air temperatures over land

A widespread decline in diurnal temperature range has been noted and discussed in the 1992 IPCC report (Folland et al., 1992) and elsewhere (Karl et al. 1993a). Hypotheses for the decline include the increasing greenhouse-gas concentration in the atmosphere, the human-induced aerosol burden and related cloudiness increases, and local changes to the heat-balance owing to urbanization. We make four points. Firstly, instrumental changes can introduce large biases (Figure 5, from Quayle et al., 1991): therefore, thorough comparisons between new and old instruments or systems are needed before the new arrangements become operational, and full documentation of changes is essential. This has not always been done in the past. Second, the analysed area needs to be extended to cover as much as possible of the land areas of the world through the acquisition of many more maximum and minimum temperature data, especially for the tropics and extratropical South America (Figure 6a). Third, an analysis period commencing in 1951 (Figure 6b) is probably too short in view of the considerations in section 2 (Figure 1). However, it may be difficult to provide a reliable data base going much further back. This is indirectly related to an apparent tendency towards higher temperature anomalies over the continents in summer in the nineteenth century (Folland et al., 1990), which may have been partly a result of differing thermometer exposures yielding higher maxima in sunny conditions (Parker, 1994). Finally the impact of changes in maximum and minimum temperatures will be as much in changes in daily extremes through the year as in mean changes. Many of the maximum and minimum temperature data readily available are, however, monthly data. A comprehensive global data set of daily data is essential. At present it is very difficult to achieve this, as a mechanism for the widespread exchange of such data sets does not exist, and many only exist in

manuscript form. Quality control of daily data also needs to be especially stringent when the emphasis is on changes in daily extremes. These are formidable obstacles to the new analyses required by policy-makers and modellers.

b) Rainfall and snowfall over land

Changes in rainfall over land are of great importance to society. Attempts have already been made to study regional trends in rainfall on a worldwide basis (e.g. Folland et al., 1990). To improve these estimates, not only are more rainfall data needed (many rainfall records remain inaccessible) but corrections are needed to the data for biases. Both theory and measurements show that, as wind speed increases, a greater proportion of precipitation fails to enter conventional rain-gauges. The effect is more marked for small droplets and especially for snow (Robinson and Rodda, 1969; Allerup and Madsen, 1980; Folland, 1988) as illustrated in Figure 7. Different designs of gauge have differing catch-efficiencies. Because gauge-designs have changed progressively, time-varying biases will have been introduced (see Figure 1 of Karl et al., 1993b). In hydrology, a serviceable correction procedure has been available for some time and also includes the effects of losses of rainfall due to wetting of the gauge collector (Sevruk, 1982). Groisman et al. (1991) have corrected precipitation data for the former USSR to compensate for these changes: the effects are marked, ie an increase of nearly 50% in the estimates of precipitation for before 1950, and an approximate halving of the apparent long-term increase (Figure 8). This arises from the large contribution of snow whose losses from conventional gauges in windy weather can be a large fraction of the incident snowfall. Clearly, careful homogenization of historical raingauge data is essential, especially in areas prone to snow or frequent high winds. This is especially important given the need to test the present-day rainfall climatology of models more stringently and predictions that rainfall is likely to increase in higher latitudes in the Northern Hemisphere as a result of greenhouse-gas-induced climate change (Gates et al., 1992).

Another requirement is for daily rainfall data measured by gauges to assess changes in extremes on daily to sub-monthly time scales. These are at present not much exchanged. Considerable data exist within hydrological rather than meteorological services. There may even be a need for sub-daily data to assess changes in the return periods of given amounts of short duration heavy rainfall important in flooding and other engineering design. These are even more difficult to obtain, though some are available for the UK and an initial attempt has been made to look at climate changes for the UK shown by short duration data (May and Hitch, 1989).

c) Marine surface winds

An apparent greenhouse-gas-related strengthening of the global hydrological cycle has been claimed by Flohn et al. (1992) and discussed in the 1992 Supplementary Report to the IPCC Scientific Assessment (Folland et al., 1992). Interpretation of the data depends to a large extent on the credence given to reported systematic increases in the strength of marine surface winds. Claims by Cardone et al. (1990) that ships' winds have been biased increasingly stronger since the 1950s, owing to inaccurate wind-speed equivalents in the 1946 WMO Beaufort scale and to the increasing use and high elevation of ships' anemometers, are supported by Ward (1992). Figure 9, based on an update of his technique, shows that wind strengths calculated from mean-sea-level pressure data do not confirm the rising trend in the observed wind strengths. These results indicate that the current mix of methods of measuring in situ wind are not satisfactory for climate change purposes without substantial attention to the data. It will be necessary to try to homogenise the earlier ships' wind data back to the 19th century (Figure 1) as well, to help make estimates of long-term changes in atmospheric circulation.

d) Mountain glaciers

There is a continuing need to monitor the length and mass-balance of glaciers worldwide. The 1990 IPCC Report (Folland et al., 1990, Warrick and Oerlemans, 1990) demonstrated the ubiquitous retreat of glaciers throughout the 20th century (Figure 10, from the first reference and Grove (1988)). This evidence was used to confirm the existence of global warming independently of the various surface temperature data sets. It was felt that this was valid because a worldwide retreat is unlikely to be related to a reduction in global mountain rainfall as this is not expected on this scale. However individual glaciers do respond strongly to rainfall changes so that a few, mostly in coastal areas, are currently strongly advancing. The importance to climate studies of worlwide glacier retreat also lies in the fact that melting of mountain glaciers is expected to contribute up to 40% of sea level rise over the next century (Warrick and Oerlemans, 1990). However, glacier data for some regions were unavailable and need to be incorporated into the global assessments: for example, the Pyrenees where glacial retreat during the 20th century has been substantial (Parker, 1993a; Tihay, 1990). Aerial photography (Hambrey and Alean, 1992) and satellite-based altimetry (ICSU/UNEP/UNESCO/WMO, 1993) are useful tools for monitoring of mountain glaciers and ice sheets. Very recent evidence (IAHS/UNEP/UNESCO, 1993) shows that retreat in 1985-1990 was at least as great as in the previous 5 year period, and many more glaciers are now being monitored, especially for their mass balance changes. Such data need to be brought together and compared carefully with worldwide regional air temperature data.

e) Radiosonde data

A good radiosonde (rawinsonde) data base is essential for input to reanalyses which are necessary to study variations in atmospheric circulation and temperature. It is also vital for use in its own right to help detect the three dimensional pattern of temperature changes expected as a result of anthropogenic influences on climate. We highlight two problems raised by Parker and Cox (1994). First, some data bases, especially those derived from monthly data transmitted in 'CLIMAT TEMP' messages, hold their winds in a mixture of units (Figure 11): the data bases need to be made self-consistent. The CLIMAT TEMP messages are to be amended from November 1994 to include a units-indicator. Second, the radiosonde data base is affected by instrumental and other changes and needs to be homogenized. Figure 12, from Elliott and Gaffen (1991), shows three heterogeneities in daytime 850 hPa relative humidities from Hilo, Hawaii. The smallest was caused by a change of observing times in 1957. A much larger bias was introduced by the adoption of carbon hygristors and a new housing in 1965 because solar heating of the new housing lowered the reported daytime humidities. In 1973, the bias was removed by the introduction of an improved housing. In order to homogenise the radiosonde data base, information or 'metadata' on instrumentation, observing hours, radiation corrections etc needs to be collected (e.g. Figure 13). In addition, WMO and other international comparisons of instruments need to be extended and used, along with models of the thermodynamics of radiosondes, to adjust the data (Parker and Cox, 1994). Even a partial attack on this difficult problem could be very valuable (Gaffen, 1994).

3.2 Satellite data

a) Atmospheric temperature

Figure 14 is a comparison of several series of annual global temperatures for 1979-1992 expressed as deviations from a 1979-89 average. Surface data as in Figure 1 are compared with radiosonde tropospheric data (850-300hPa) updated from Angell (1988), a separate 850-300hPa series from Oort and Liu (1993) based on more complete radiosonde data but only extending to 1989, and Microwave Sounding Unit (MSU) tropospheric data from Spencer and Christy (1992) representative of approximately the same region of the troposphere. As can be seen from Figure 1, the beginning of

this period comes towards the end of the warming "jump" of the mid to late 1970s. The period shows some warming in the surface and radiosonde data but none in the MSU data. However any trends are superimposed on considerable interannual variability associated with two major El Nino - Southern Oscillation (ENSO) warm events (1982-3, 1986-8) and a major ENSO cold event (1988-9), as well as the cooling due to the eruption of Mount Pinatubo in 1991-2 which appears to be larger in the troposphere than near the surface. The enhanced variability in Angell's data relative to Oort and Liu's is partly a result of the sparsity of Angell's network (63 stations in toto) compared with Oort and Liu's network (typically near 800 stations). Some of the relative cooling in the MSU record might result from changes in satellite crossover-times (Folland et al., 1992), but this is uncertain. There are likely to be real physical differences between all three measures. Thus the amplitude of the interannual variability of the surface and mid-troposphere is not the same (Trenberth et al, 1992). The likelihood that the cooling due to Mt Pinatubo was larger in the troposphere than at much of the surface (e.g. the thermally sluggish oceans and coastal land areas) will significantly affect the trends over this short period. The fact that the MSU has truly global coverage and the other series do not is also a major factor, in favour of MSU. The surface data can be made more complete by including blended satellite SST data, and this has been done in a preliminary way for the period since 1982 (Parker et al.,1994). However, the fact that a mid-tropospheric data set cannot completely replace a near surface data set for monitoring surface temperature itself means that the MSU data are not a replacement for the surface data. It would be interesting, though, to create as complete as possible a **near-surface** radiosonde temperature data set for a level just above likely urbanisation problems, and compare trends in these data with those from approximately colocated surface (land air temperature and SST or night marine air temperature) data. To achieve this, it would be essential to select radiosonde data sampled at fixed local times.

In the meantime, apparent differences between trends must be treated with caution. The possibility that there is a residual artificial warming bias in the land and SST data between 1979 and 1992 cannot be discounted, though it cannot easily be more than a few hundredths of a degree (Jones et al., 1990; Folland et al., 1992; 1993). Clearly a more detailed comparison of these data is needed, with a more rigorous attempt to quantify time-variable biases in the non-MSU data, which are liable to result as much from time-variable coverage as from instrumental problems.

MSU data of a different wavelength have also been used to monitor lower stratospheric temperature since 1979 (Spencer and Christy, 1993). The data are much more complete than from radiosondes and their value is enhanced by the likelihood that time-varying biases in radiosondes are likely to be greater at this level. Again, more detailed comparisons are needed.

b) Sea ice and snow cover

Satellite data of sea-ice extent are important because changes in sea-ice extent can have large regional effects on temperature. Model predictions indicate that sea ice extent will markedly diminish as a result of greenhouse-gas-induced climate change so these changes may be a sensitive indicator of warming. Figure 15 shows the historical record of global mean sea-ice extent since 1973. However, doubt has been cast on the homogeneity of the later data with those for 1973-6, which were largely based on a microwave radiometer which differed from, and did not overlap with, later instruments (Parkinson, 1992). Because it began in 1973, the usable global record gives a limited historical perspective (section 2 and Figure 1) and the signal of long term trends is likely to be dominated by the noise of decadal variability.

Sea-ice extent data alone are insufficient: thickness also needs to be monitored, if climatic variations of sea-ice are to be properly understood. Under the Arctic Climate System Study (ACSYS) (ICSU/WMO/IOC/SCOR, 1992), sea-ice thickness data are

being acquired from upward-looking sonars moored mainly in the Fram Strait, where sea-ice leaves the Arctic basin, and from submarines on transects. Historically, the availability of submarine-based sonar data has been restricted by military classification: the sparsity of the available measurements has made it impossible to distinguish interannual variability from any longer-term trends, and there is not even a reliable baseline climatology because the submarines have taken different routes in different seasons through sectors with widely differing ice conditions (Folland et al., 1992). Also,different instruments may have different biases and precision (ICSU/WMO/IOC/SCOR, 1992). The record from the moored sonars is still only a few years long (ICSU/WMO/IOC/SCOR, 1992).

The problem of a short record also applies to satellite-based monitoring of snow-cover extent variations. Nevertheless annual values over the Northern Hemisphere north of 30°N corrrelate (inversely) quite strongly with annual surface temperature variations over the same region (Figure 16). Robinson et al. (1993) present a slightly improved record of Northern Hemisphere snow cover and discuss the potential developments in monitoring of snow, while stressing the importance of maintaining a record which is consistent with existing satellite-based analyses. Again a marked reduction of Northern Hemisphere winter half year snow cover, especially in autumn and early spring, is predicted to result from greenhouse warming so this is likely to be another sensitive indicator of climate change. Such changes might be dominated at first, of course, by shorter time-scale atmospheric circulation changes.

Ideally, a mixture of satellite and surface data should also be used to develop a global data set of snow **depth.** This is very desirable for fully understanding the changes in snow cover extent that occur, quite apart from their value in hydrological studies. Passive microwave satellite data have already been used by Goodison and Walker (1993) to assess interannual changes of snow water equivalent over the Canadian Prairies.

c) Aerosol optical thickness

Aerosol optical thickness has recently become a very important quantity as it is now believed that forcing due to anthropogenic, mainly tropospheric, aerosols is partly offsetting the forcing due to increased greenhouse gases (Isaksen et al., 1992). Stratospheric aerosols have also increased in importance mainly because measurements after the eruption of Mt Pinatubo have shown conclusively that such volcanic eruptions can cause a large negative radiative forcing on climate even if only for a relatively short time (Minnis et al., 1993). In addition, anthropogenic sources may have contributed to recent increases of stratospheric aerosol (Hofmann, 1990). Stratospheric aerosols have been monitored by the NASA Stratospheric Aerosol and Gas Experiment (SAGE) radiometers. These measure vertical profiles of aerosol - related radiative extinction in the atmosphere by viewing the sun during sunrise and sunset as observed from the satellite (Minnis et al., 1993). Figure 17, from NOAA (1992), is included to illustrate the ability of this satellite instrumentation to monitor atmospheric aerosol. The stratospheric aerosol veil from Pinatubo was largely confined to the tropics (light solid line) in the first few months after the eruption. By the end of 1991, however, the stratospheric circulation had spread the aerosol to higher latitudes of the Northern Hemisphere (heavy solid line). The stratosphere in middle latitudes of the Southern Hemisphere (dashed line) may have been affected by the eruption of Cerro Hudson in Chile in August 1991. As mentioned in section 3.1, tropospheric aerosols may have contributed to the increases of minimum relative to maximum temperature that are quite widely seen. The most useful single data set might be of computed combined radiative forcing at the surface from tropospheric and stratospheric aerosols, as spatially complete as possible, on an annual or even seasonal time scale.

d) Ozone

The reductions in stratospheric ozone that have been observed almost worldwide, and most dramatically in the Antarctic ozone hole, have resulted in ozone becoming an important variable from a climate change perspective (Isaksen et al., 1992). The climatic effects of a reduction in ozone can be complex: a reduction in greenhouse forcing, adding to the negative radiative forcing effect of aerosols; changes in the absorption of solar radiation; and consequent changes in the dynamics of the global atmospheric circulation which are currently little understood. In addition, an increase in greenhouse gases may accelerate ozone depletion through a cooling of the stratosphere which could make the reactions involving chlorofluorocarbons more likely to take place and for a longer period of the year: on this basis, Austin et al. (1992) have demonstrated the possibility of an Arctic ozone hole in a doubled CO_2 climate.

Satellite measurements of ozone began in 1970 with the Solar Backscattered Ultraviolet (SBUV) instrument (Heath, 1988). The Total Ozone Mapping Spectrometer (TOMS), which monitors the earth's albedo in the ultraviolet, has operated since 1978 (Stolarski et al., 1992). SAGE solar occultation data (see also the section on aerosols) have been used to measure ozone in 1979-1981 and from 1984 onwards. Figure 18, also from NOAA (1992), documents the dramatic development of the Antarctic ozone hole. A long historical perspective is, of course, missing, despite surface-based data from a network of Dobson near-ultraviolet spectrophotometer stations mainly from 1957, filter ozonometers in the former Soviet Union from 1973, ozonesondes from a sparse network of stations since the late 1960s, and Umkehr ozone profiles, based on zenithal ultraviolet radiance at sunrise and sunset, at ten stations since the late 1970s (Stolarski et al., 1992). However in view of the fact that substantial ozone trends are probably largely man made, a long perspective is less important. The combined satellite and ground based record is now becoming long enough to distinguish the recent trend from other known effects on interannual ozone amount, e.g. the sunspot cycle, even in some areas outside the ozone hole.

e) Rainfall

The quantitative measurement of truly global rainfall trends has up to now been impossible because of lack of data over the oceans, though useful attempts to produce rainfall climatologies over the oceans have been made (e.g. Jaeger, 1983; Legates and Willmott, 1990) and are used by modellers. Only small changes in globally averaged rainfall are expected to result from greenhouse gas forcing so the emphasis is on regional changes, partly associated with changes in atmospheric circulation. Over the ocean the only feasible methods are likely to be satellite based, possibly calibrated with a restricted set of surface based sensors (see ICSU/IOC/WMO,1993 for discussions). Since the mid 1970s, outgoing longwave radiation (OLR) measured from satellites has been used to estimate precipitation in areas of tropical convection (Arkin and Meisner, 1987), but heterogeneities in the data have made them inadequate for climate change studies (see discussion in Folland et al., 1990). One major problem is inconsistency between instruments on different satellites (Janowiak, 1993). Very recently Spencer (1993) has proposed a new method which uses the same polar orbiting satellites' microwave sounding units as have been used to deduce tropospheric and stratospheric temperature trends, but choosing a different mix of wavelengths. The initial results look promising.

f) Vegetation

The use of satellite data to monitor vegetation is a key element of the International Satellite Land-Surface Climatology Project (ISLSCP) reviewed by Becker et al. (1988). A Normalized Difference Vegetation Index (NDVI) has been developed, characterizing the state of vegetation by the relative reflectances of near-infrared and red or visible radiation. This is necessary because future climate changes and vegetation changes may interact regionally, whether the vegetation changes are due to climate

change itself or the more direct effects of man's activities. In addition our understanding of the mean annual cycle of the current climate, and its depiction in models, requires that these data be collected. Blumel et al. (1988) presented monthly fields of NVDI for central Europe for 1983-1985. A microwave-based vegetation index has also been developed (Choudhury and Tucker, 1987). Interannual and annual vegetation changes in areas such as the Sahel are clearly shown by both techniques (Becker et al.,1988).

g) Cloud

Truly global monitoring of cloud has only become possible with the advent of the satellite era. Diverse satellite data have been collated and analysed under the aegis of the International Satellite Cloud Climatology Project (ISCCP), which is reviwed by Rossow and Schiffer (1991). However, there are systematic biases in radiances measured from different satellites, and the calibrations of individual instruments also undergo drifts. A major part of the ISCCP has therefore been to make the data homogeneous (Rossow and Schiffer, 1991). There are also systematic differences between satellite-based and ground-based estimates of cloudiness (e.g. Figure 7 of Rossow and Schiffer, 1991). These differences, and heterogeneities in ground-based estimates of cloudiness (e.g. Karl and Steurer, 1990), need to be taken into account in the construction of longer-term local and regional time-series of cloudiness. In the meantime we regard these data as being more suitable for process studies and studies of interannual variability than climate change. However the urgent need for a homogeneous cloudiness data set in climate change studies is shown by the current speculation that observed relative increases of maximum compared to minimum continental surface temperatures are, in part, related to changes of cloudiness over land (section 3.1a).

h) Combined satellite data bases

Several of the abovementioned satellite data sets, including the TOVS and the Geostationary Observational Environmental Satellite (GOES) Visible and Infrared Spin-Scan Radiometer (VISSR) which is a key element in ISCCP, are included in the PATHFINDER data base being built by the USA's National Oceanic and Atmospheric Administration (NOAA) and National Aeronautics and Space Administration (NASA) (Booth and Maiden, 1993). The PATHFINDER data base is characterized by improved calibration, consistently-applied algorithms, global coverage, and "long" time-series, extending back to 1978 for VISSR. Within the constraints of a 15-year time series (Figure 1), this data base is expected to prove a valuable tool in climate research. Although it will be most useful for interannual variability studies in the medium term (which contribute indirectly to ideas about climate change), any appreciable extensions of the PATHFINDER data base in the future will start to make it long enough for monitoring trends if the data can be made sufficiently homogeneous. Release of the data is expected to start in 1994.

3.3 Blended data

a) SST

Our first example of the advantages of blended data relates to SST. As already stated in section 2, volcanic aerosol-induced biases in satellite-based SST have been removed by blending with in situ data. Figure 19, from Folland et al. (1993), illustrates this for the period following the April 1982 eruption of the Mexican volcano El Chichon. The blending technique of Reynolds (1988) yields a time-series of Northern Hemisphere blended SST anomalies very similar to that based on in situ data alone, despite the severe biases in the satellite data used in the blending. The advantage of the blended over the in situ analysis is its greater geographical coverage which opens up the possibility of minimising the influence of data gaps on assessed climatic trends over the ocean and, when enough data have been collected,

adequately assessing trends and variations over the Southern Ocean for the first time. This expansion in coverage is illustrated in Figure 20 which compares the Meteorological Office in situ 'MOHSST5' coverage for January 1989 with the Global sea-Ice and Sea Surface Temperature (GISST) coverage for the same month. GISST1.1 incorporates satellite-based SSTs via a slightly modified version of the Reynolds (1988) blending technique, along with satellite-based sea-ice coverage (Parker et al., 1994)). Further improvements in the analysis of such data are needed as indicated in the concluding section of Reynolds and Marsico (1993).

b) Rainfall

The only feasible way to obtain a global data set of rainfall is to blend conventional surface based data over land and islands with suitably calibrated satellite data over the ocean. In the longer term, analyses from weather forcasting models run in reanalysis mode may add further genuine information during the complex blending process. Indeed, rainfall derived from the European Centre for Medium-range Weather Forecasts (ECMWF) model is already being used experimentally as a major oceanic input in higher latitudes in the new GPCP data set (ICSU/IOC/WMO, 1993 and Rudolf, 1993) that starts in 1986. However, such data are unlikely to be homogeneous. Because rainfall is crucial to understanding atmospheric circulation changes and the associated processes, a globally-complete, homogeneous data set is urgently needed. The new technique described by Spencer (1993) that uses MSU data (section 3.2(e)) has been calibrated to an extent using island data chosen where topographical effects are considered small. This opens up the possibility of a historic blended satellite/land data set extending back to 1979. The feasibility of combining land raingauge data, outgoing long-wave radiation data and microwave data from the Special Sensor Microwave Imager (SSM/I) on a daily basis has been explored on sample data by Gairola and Krishnamurti (1992) using a blending procedure. Their main motivation is the estimation of diabatic heating from precipitation to better initialise weather forecasting models. The results shown in their paper appear to offer a distinct promise of a global sub-monthly rainfall data base over the oceans. This is needed for the studies of low frequency weather variability (such as the 40-60 day oscillation) that must underpin crucial parts of the strategy needed to understand climate change.

Future plans for global data collection include the use of satellite-based rainfall radar in the Tropical Rainfall Measuring Mission (TRMM), briefly summarized by Thiele (1993). In the meantime, local and regional rainfall data bases are being improved by, for example, applying seasonally and geographically varying calibrations to satellite-based infrared images using conventional raingauge data, as in the Sahel by the TAMSAT method of Flitcroft et al. (1989).

3.4 Subsurface ocean data

From a climate change detection perspective, there are two main interests. The first lies in the possibility that global warming could be detected with good statistical significance in the deeper oceans, beneath the reach of the seasonal cycle, because the interannual variability of temperature is thought to be very low there. Even very small changes of a couple of tenths of 1°C may be detectable as a trend. The second interest lies in the possibility of significant changes in ocean circulation e.g. a slowing of the Atlantic thermohaline circulation. The major data required are temperature and salinity and some current velocity data, though many data will have to be derived from the assimilation of temperature and salinity data into ocean models. Recently Leetmaa and Ji (1989) and Foreman(1992) have developed assimilation techniques for subsurface data using ocean models, though these are more directed at initiating seasonal or shorter-term predictions and understanding interannual oceanic variability. A calculated time-longitude section of the depth of the 20 °C isotherm along the equator in the Pacific Ocean during 1990-1992 is shown in Figure 21. In view of the sparsity of the observations, model assimilation of the data was

essential, though there will then be some model-dependence in the results. See also the review by Smith (1993).

Continuation and development of the TOGA and WOCE observing networks in support of CLIVAR is essential (see section 1). Data needed especially include expendable bathythermographs (XBTs) (ICSU/UNEP/UNESCO/WMO, 1993). Temperatures in the deep ocean may be derived from acoustic tomography (Munk, 1989; Wunsch,1992). In this proposed technique, the transit time of a sonic pulse is used to assess the mean temperature of the water along the track from transmitter to receiver. However, this method only gives a coarse spatial resolution.

Preliminary attempts to detect warming in restricted regions of the deep ocean have already been made from XBT and hydrographic data. Antonov (1993) detected an apparently significant warming below 600m in the North Atlantic between 1957 and 1981, more than compensating for the cooling in the upper layers (Figure 22). In the North Pacific, however, although the top 700m cooled, there was little change at greater depths. Bindoff and Church (1992) found depth-averaged warming of up to 0.04°C between 1967 and 1990 on sections in the Pacific Ocean between Australia and New Zealand. Data sparsity hindered both these investigations, showing the need to continue and expand the WOCE networks. Ellett and Blindheim (1992) used more plentiful data to report on hydrographic variability in the upper layers in part of the North Atlantic in the 1980s.

3.5 Model-assimilated data and calculated data

The need for homogeneous model-based reanalyses was stressed at the end of section 2. Another need is for *compatible real-time analyses*, i.e. the same, or at least similar, model(s) as used for the reanalyses must also be run operationally, though possibly with a slight delay relative to operational weather forecasting requirements, in order to allow the use of delayed data. NOAA have plans to do this, with a higher resolution model than is likely to be used for much of the reanalysis (E.Kalnay, pers. comm).

Good reanalyses will provide model diagnostics which, with the current development of theory in this area (review in Palmer, 1993), should allow a much improved understanding of climatic 'phenomena', and thereby lay the groundwork for assessing how these may change both naturally and in response to anthropogenic forcing. These changes may not be linear and any appreciable changes in the frequency or character of regional weather types will have a major impact on changes in regional extremes in addition to the gross effects of any global warming. A good example of a "natural variability" of this type concerns the winters over North West Europe this century (e.g.Parker and Folland, 1988). Early this century when much of the globe, including parts of the N Atlantic, was cooler than the (1951-1980) normal, winters in North West Europe were warmer and extreme cold was rare, owing to a lack of blocking or, on an alternative view, an increase in the frequency and possibly strength of weather patterns mimiced by the positive phase of the "North Atlantic Oscillation". As a result many nineteenth century records of extreme winter cold in the UK were only closely approached or exceeded again after 1940, with exceptionally notable examples of cold as recently as 1982 (winter minimum temperatures) and 1987 (winter maximum temperatures), despite increases in greenhouse gases.

As implied in section 3.3 above, another benefit of good reanalyses will be an improved knowledge of rainfall over the oceans, vital to understanding the character of the hydrological cycle and monitoring expected changes in its vigour.

Other quantities probably only reliably calculable in the longer term from reanalyses, except for some local exceptions, are heat fluxes at the ocean surface, atmospheric mass and moisture divergence, vorticity, diabatic heating, and, with the aid of ancillary hydrological and vegetation models, soil moisture. Data alone cannot estimate

divergent quantities such as divergence itself or velocity potential. As an example of what is possible now, monthly mean 200 hPa divergence changes over West Africa, according to operational analyses of the ECMWF, matched Sahel rainfall changes between August 1989 and August 1991 (Figure 23). However many changes have occurred in the formulation of this model so that time series of such quantities, or diabatic heating, with which they are related, are seriously heterogeneous (Trenberth and Olson, 1988). Reanalysis with a single model and assimilation system will overcome this.

4. CONCLUSIONS

We have selectively illustrated shortcomings of existing data from a climate change perspective. We have also identified likely or desirable improvements in them using a wide range of stand-alone and assimilated variables that are needed for thorough-going monitoring of climate and the detection and attribution of climate changes over the next one to two decades. Homogeneity is the most crucial factor and is closely bound up with a need for global completeness. More attention is needed to the development of adjustment methods to make past data as homogeneous as possible and to ensure that the increased contributions of satellites do not compromise homogeneity.

As stated in the Report of the 1990 Second World Climate Conference and in the current plans for GCOS (ICSU/UNEP/UNESCO/WMO, 1993), it is clear that no truly global climate-monitoring system yet exists with adequate spatial resolution and accuracy for almost any variable. Nevertheless, implementation of the approaches discussed, already reflected in the GCOS plans, will remedy the situation sufficiently to put the monitoring of climate change on a more reliable footing. This will provide a good chance that at least some climatic variations and changes over the next twenty years will be detected fairly reliably. Attribution of the changes depends, of course, on major developments in understanding the causes of variations. Improvements in data hand-in-hand with improvements in models are expected to accelerate these developments.

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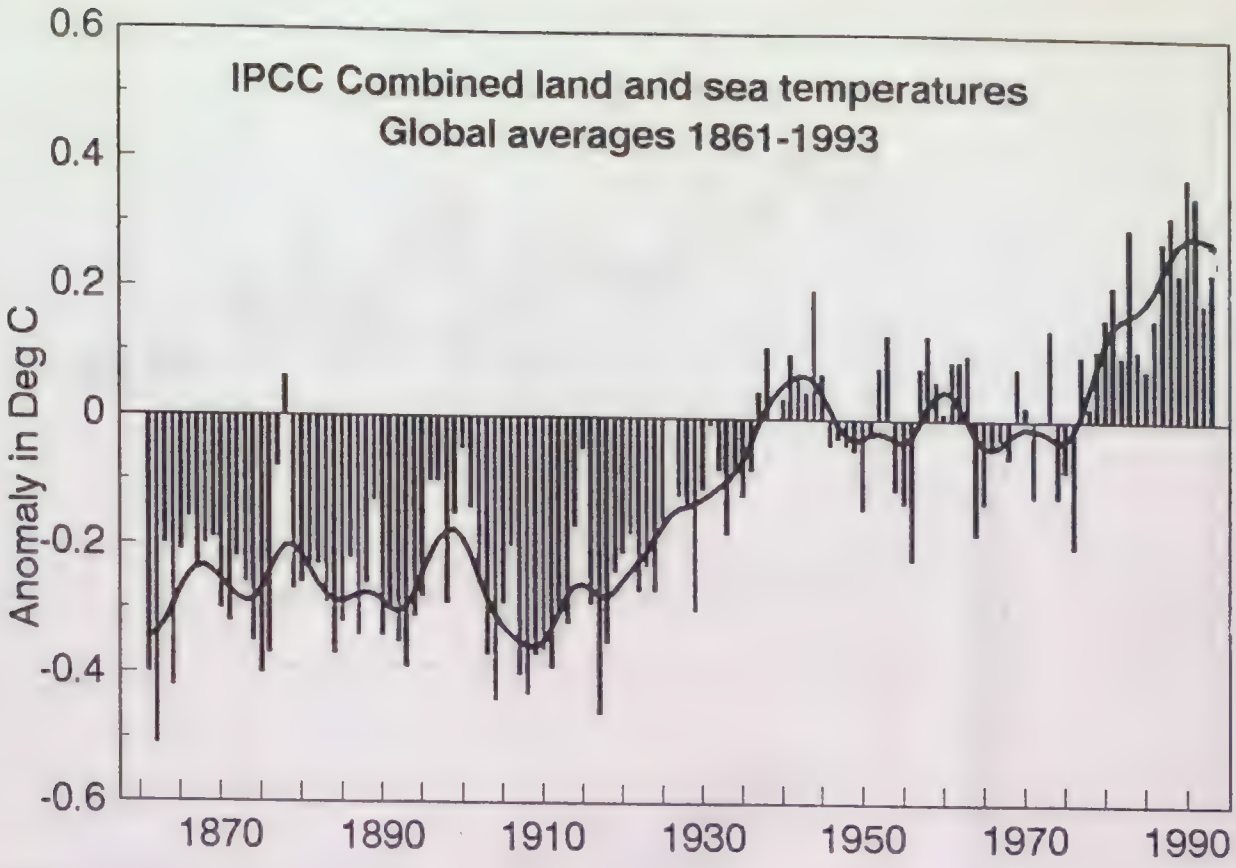

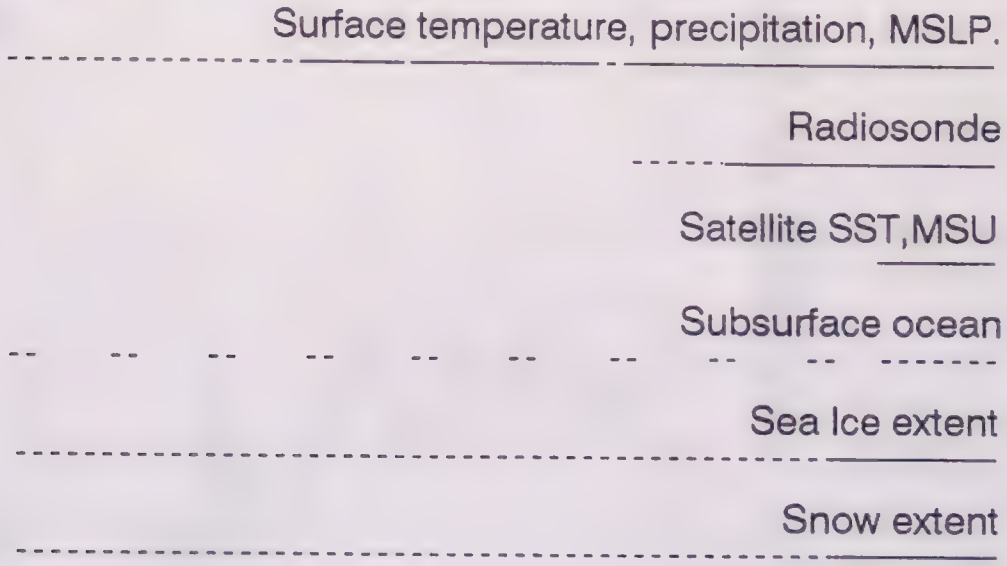

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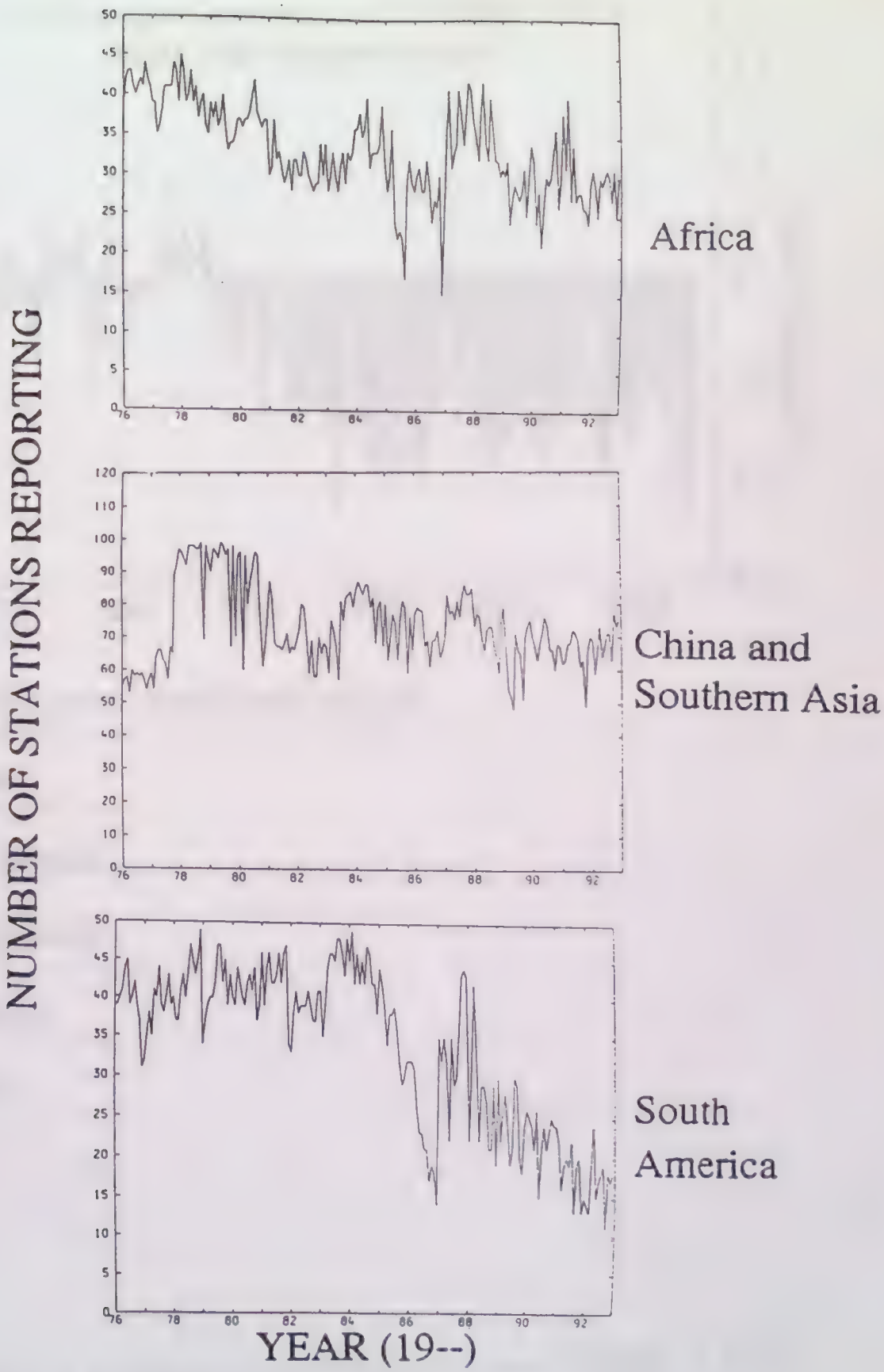

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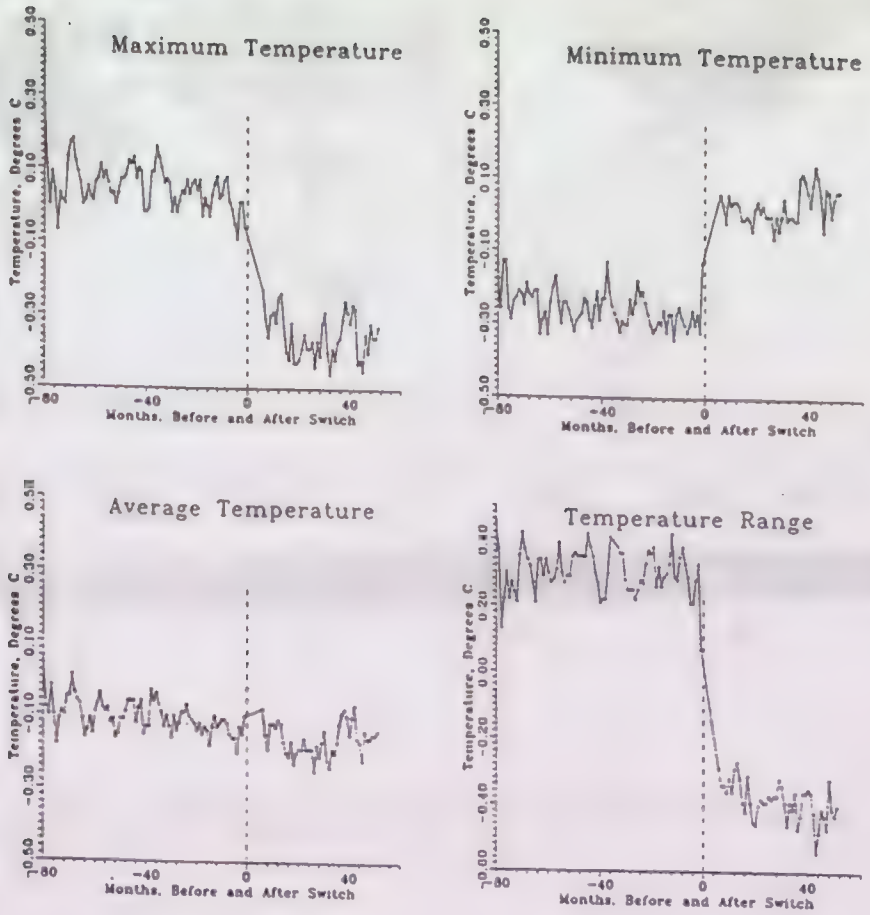

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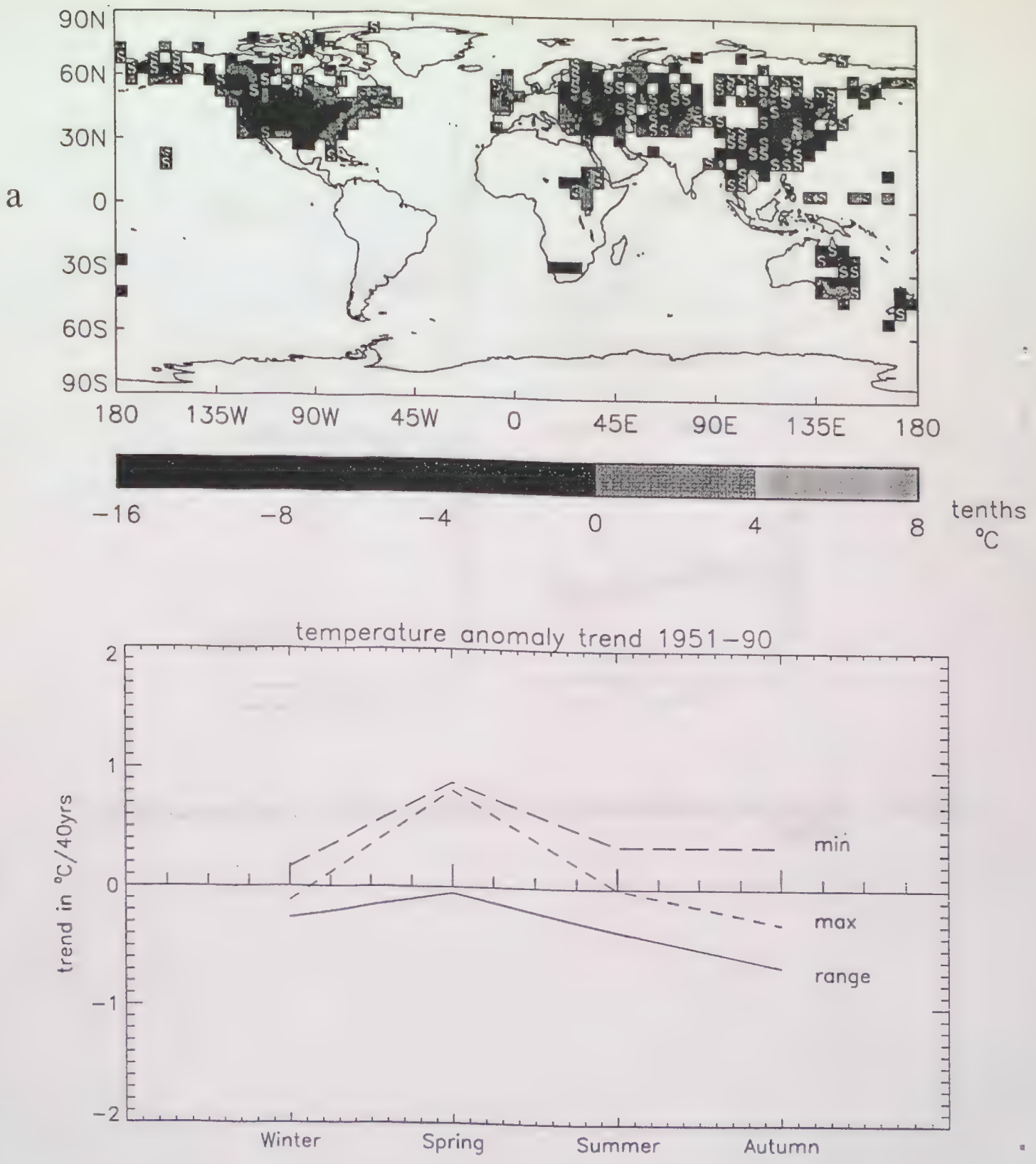

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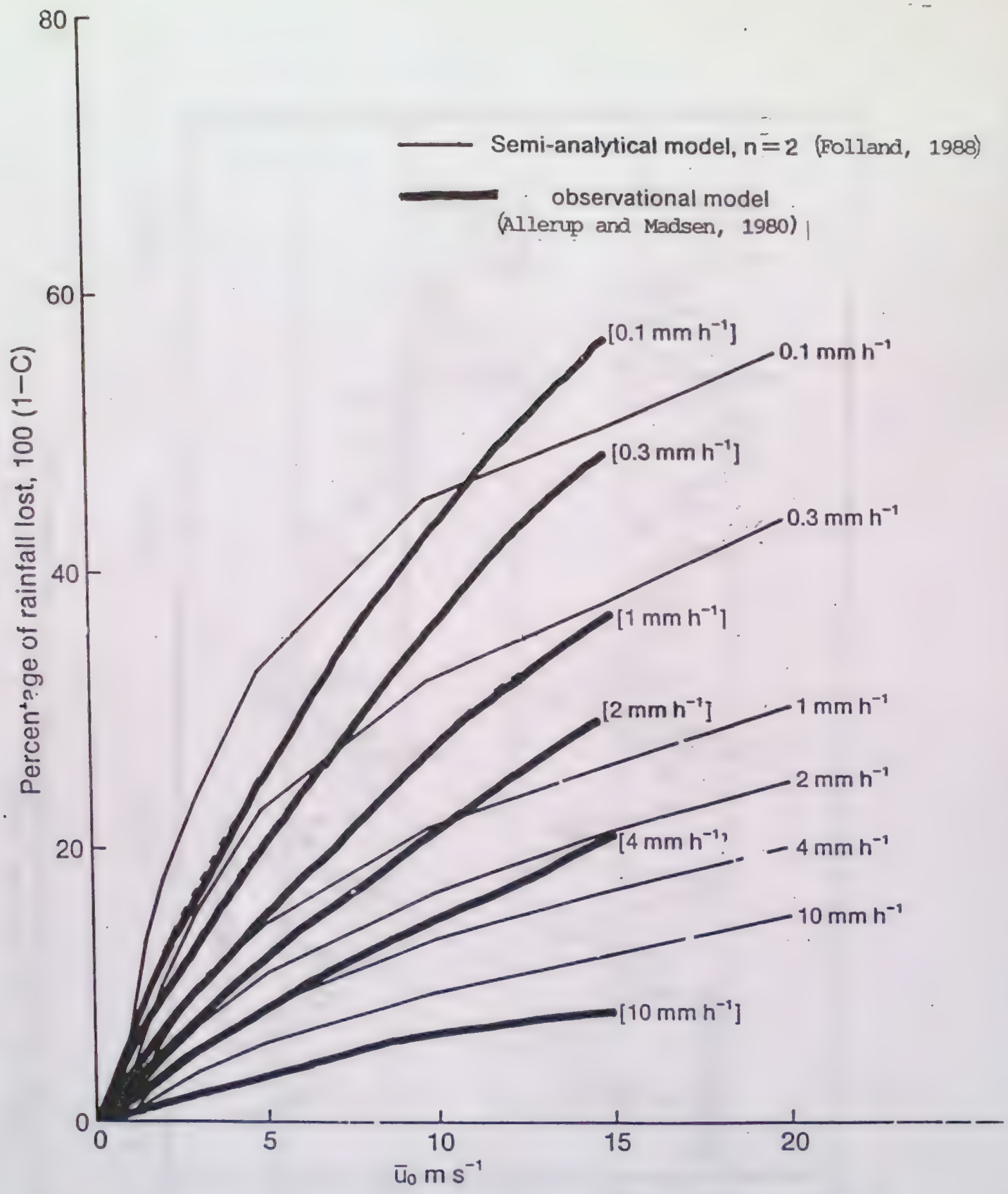

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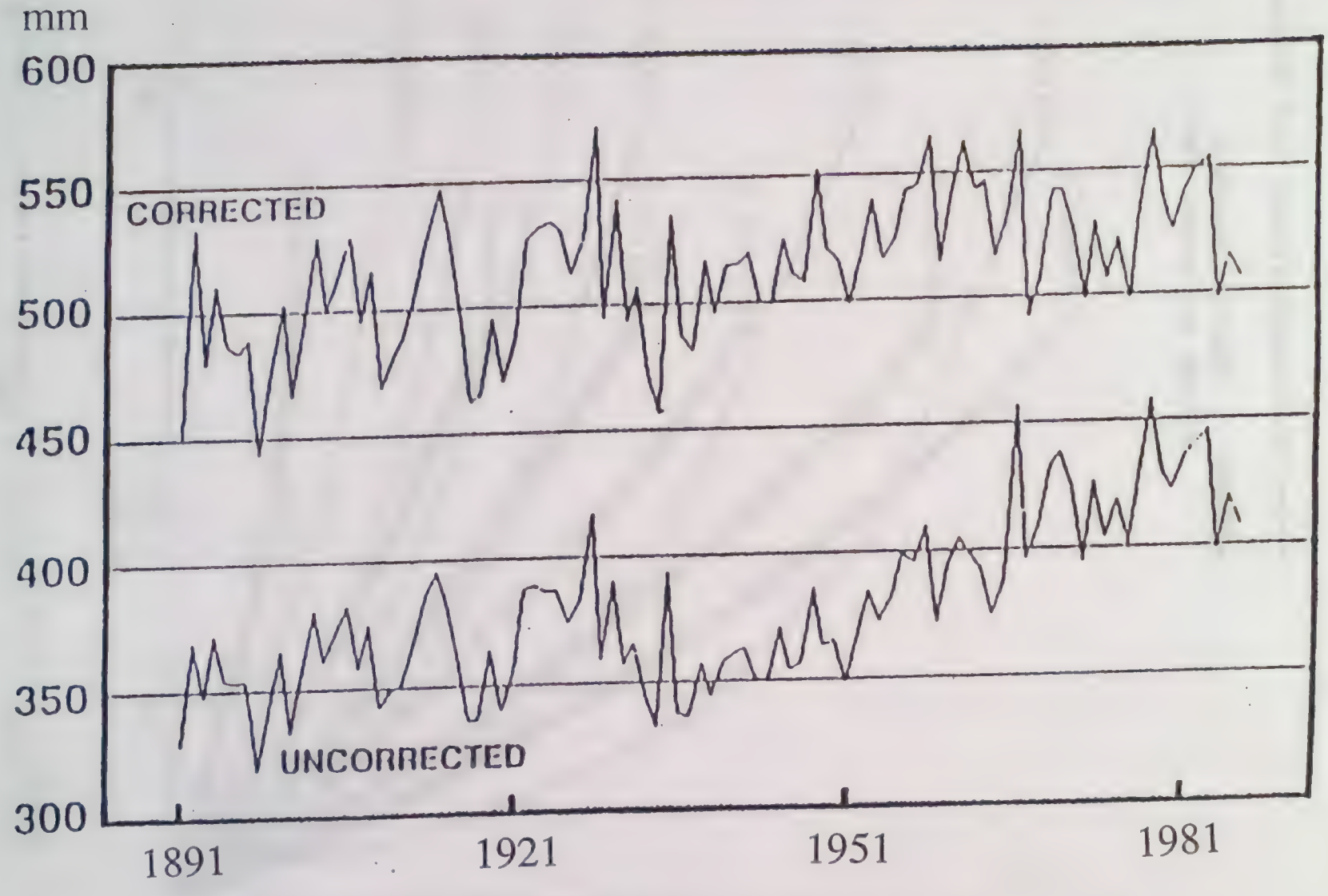

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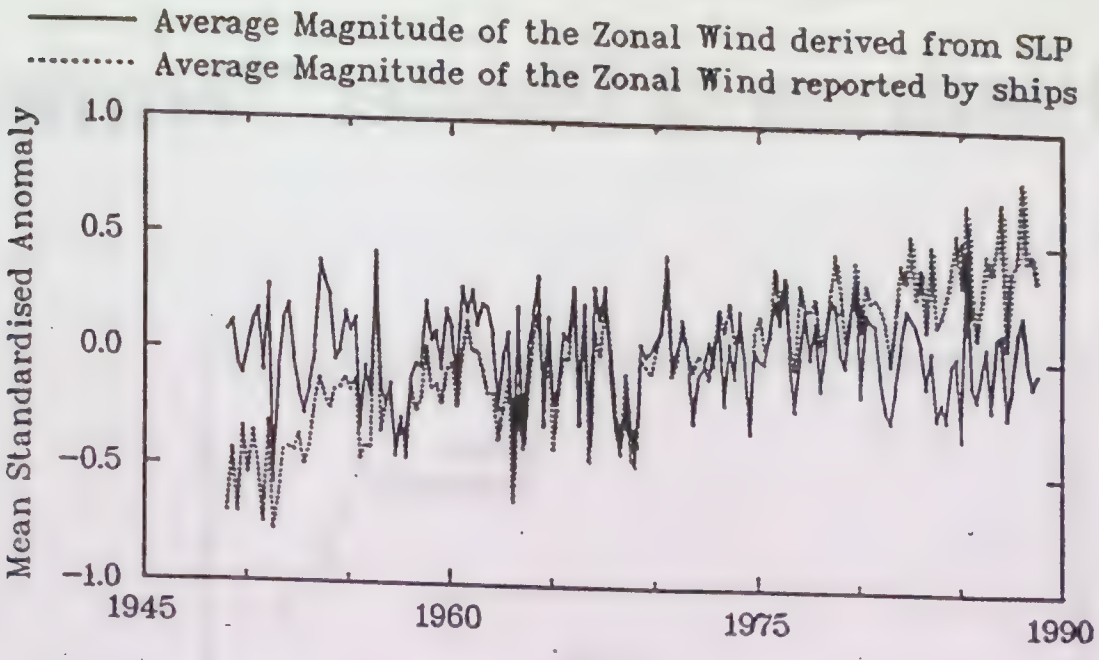

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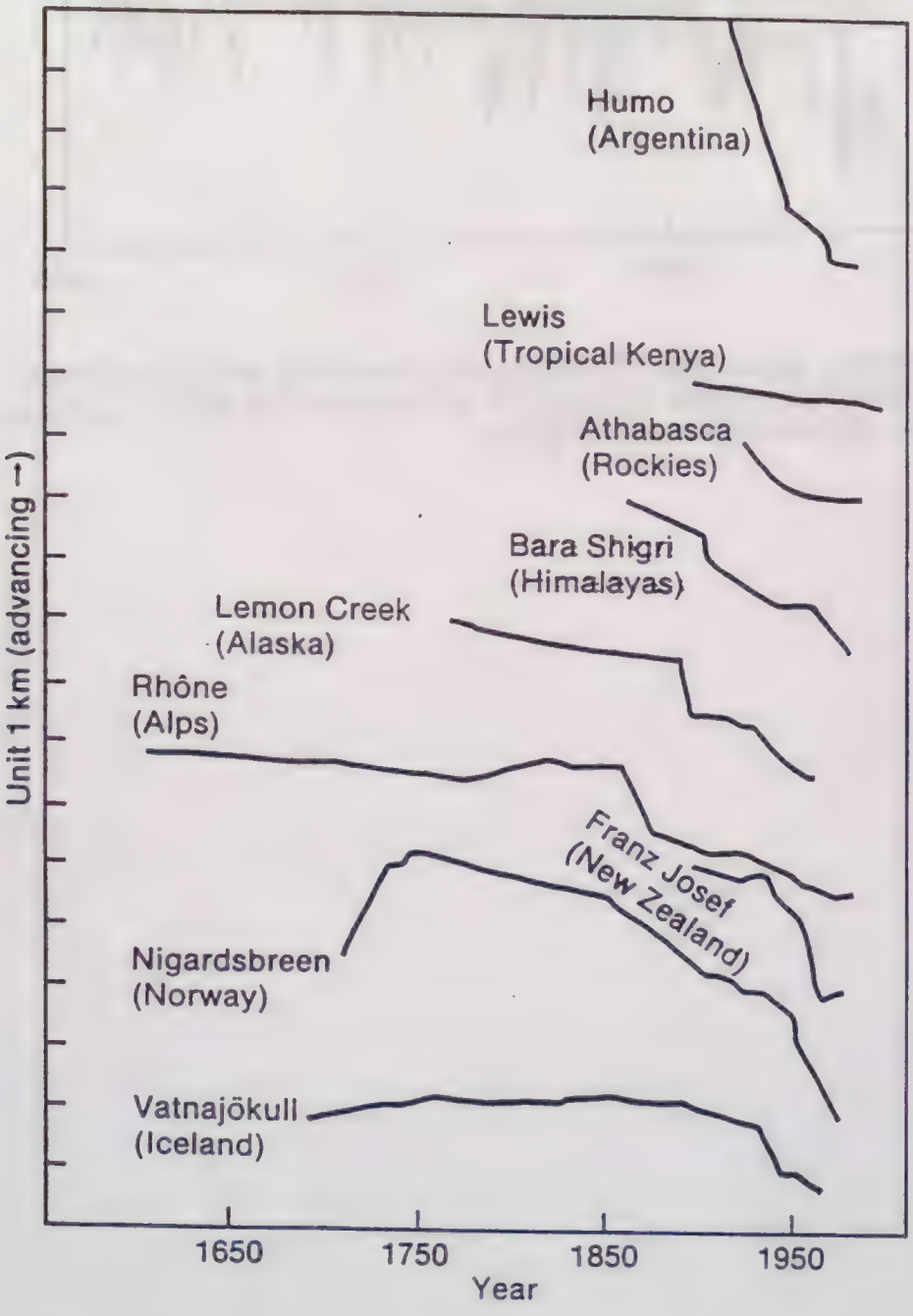
Fluctuations of Glacier Termini



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Upper air plot for January 1988 at 300 hPa

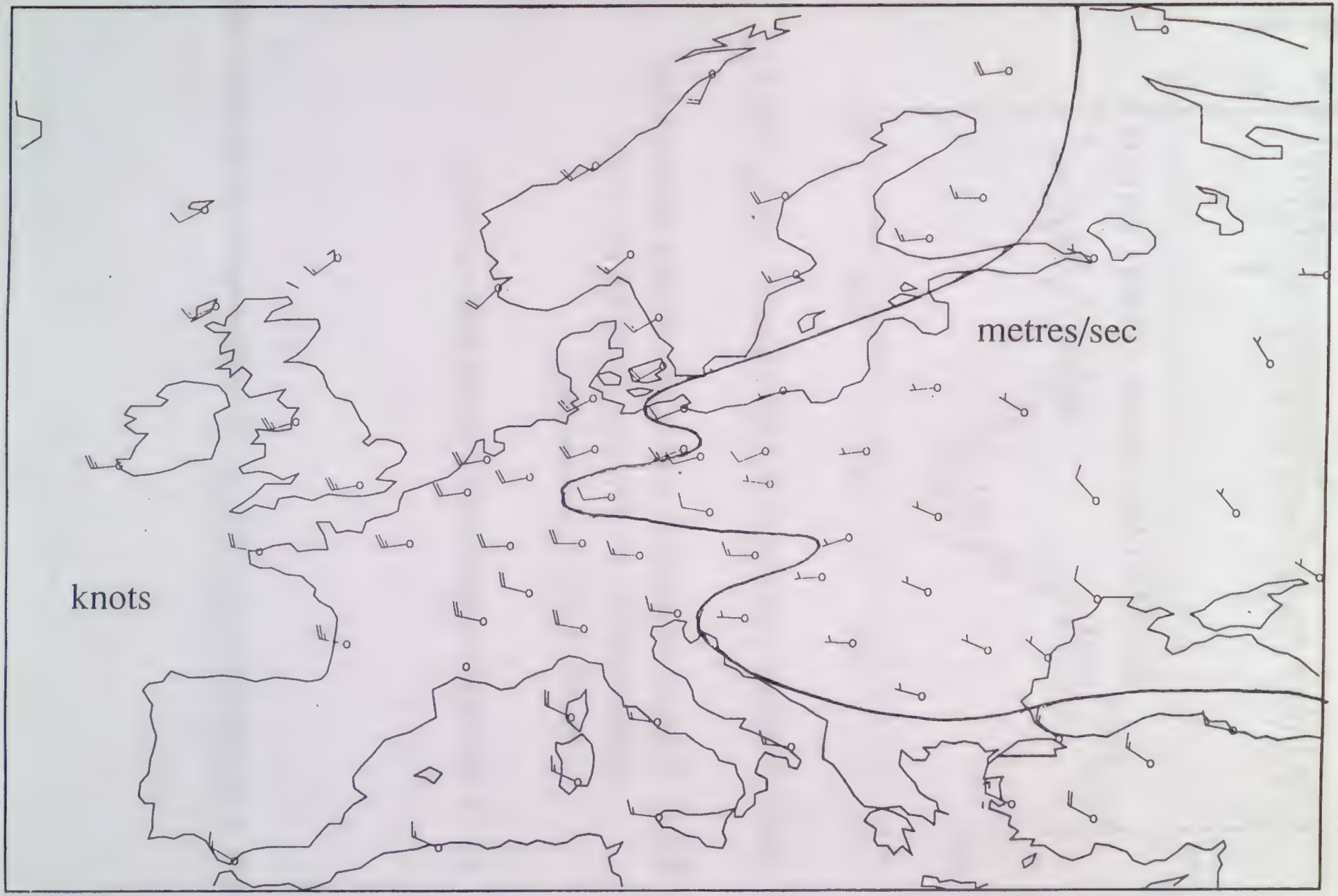
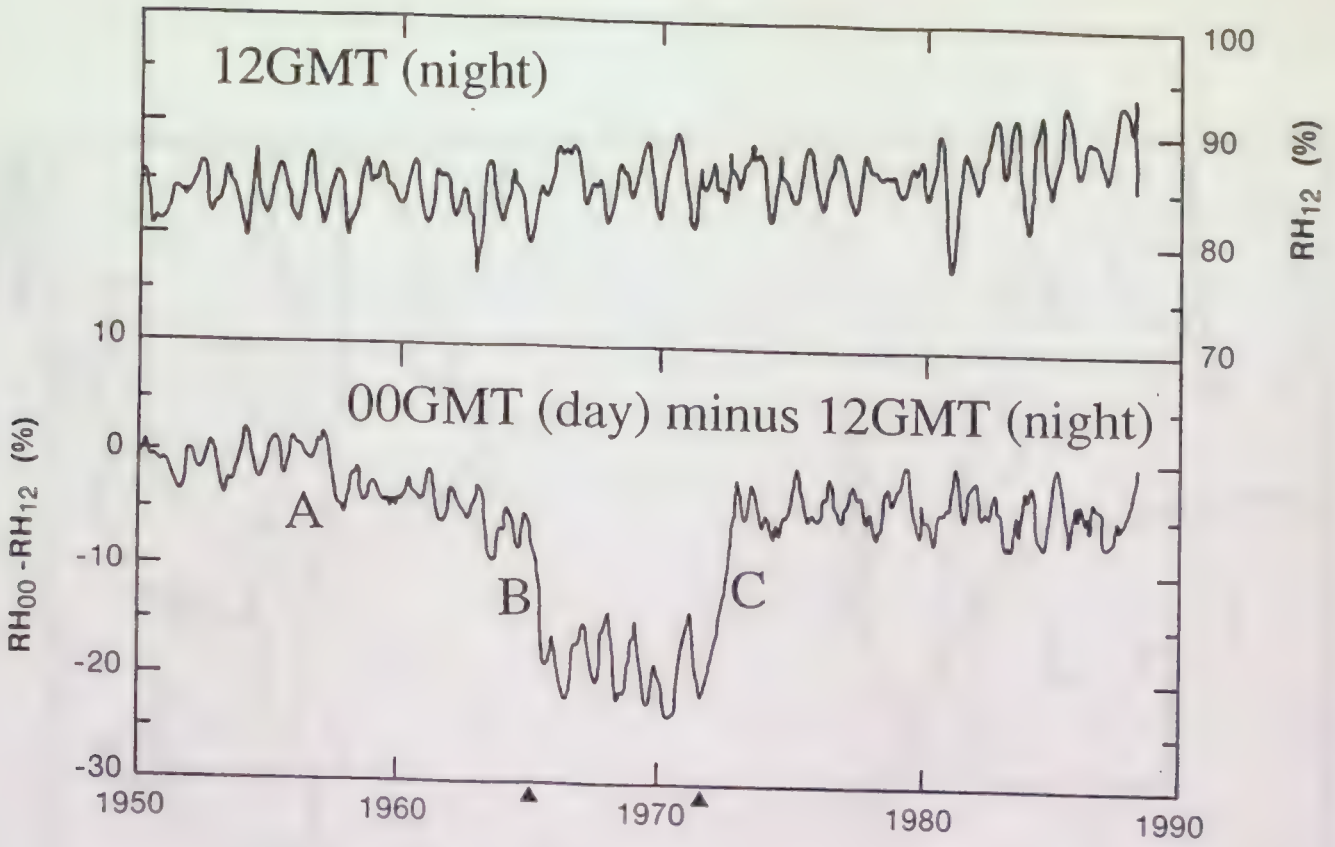


Figure 11 Reported monthly 300 hPa winds, January 1988.

M.P.O'Donnell
July 1993



A 1957 Sounding times changed from (03,15) to (00,12)

B 1965 Carbon hygristors and new housing introduced. Solar heating of housing lowered reported daytime relative humidity.

C 1973 Housing improved to avoid solar heating.

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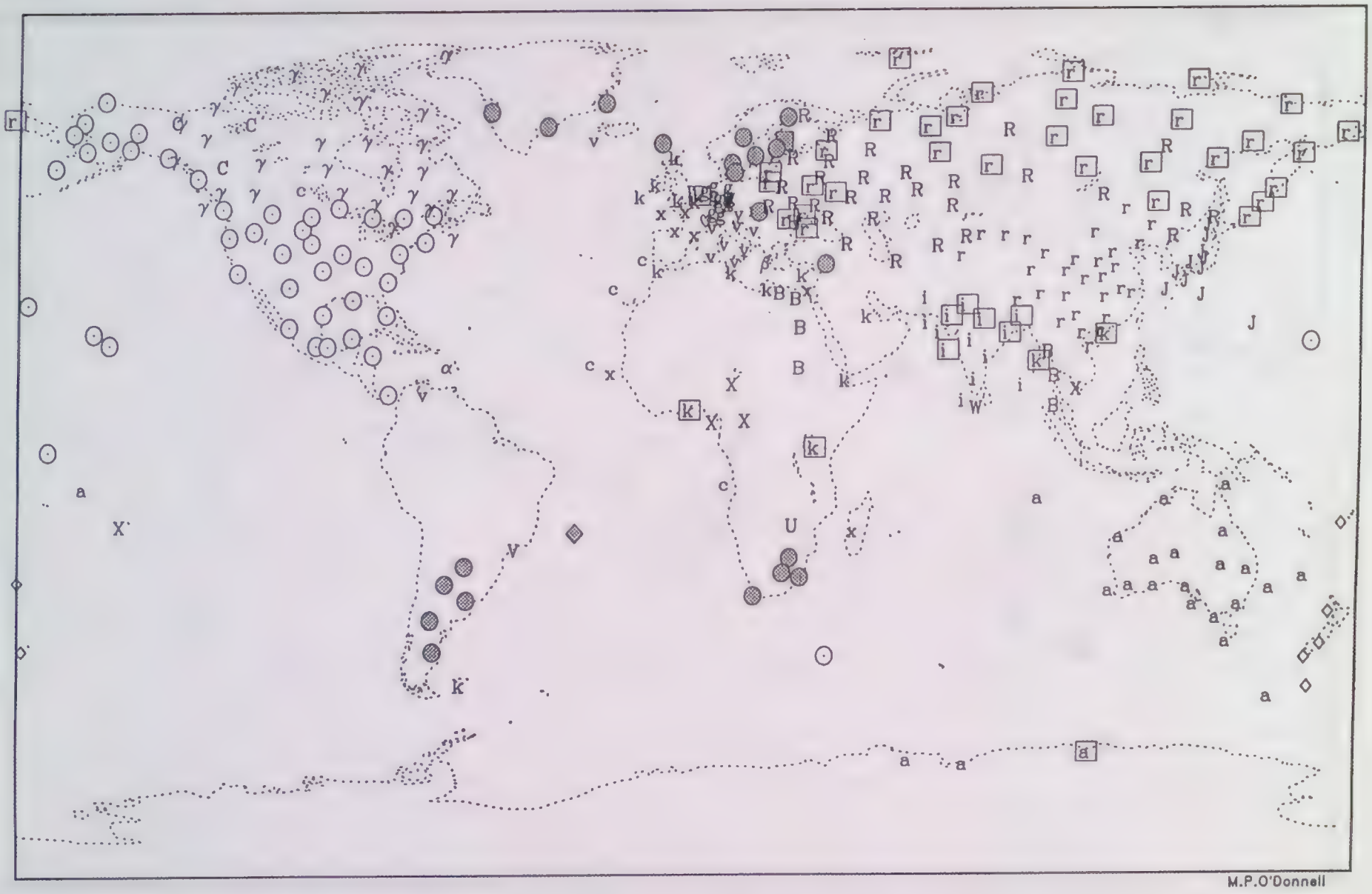

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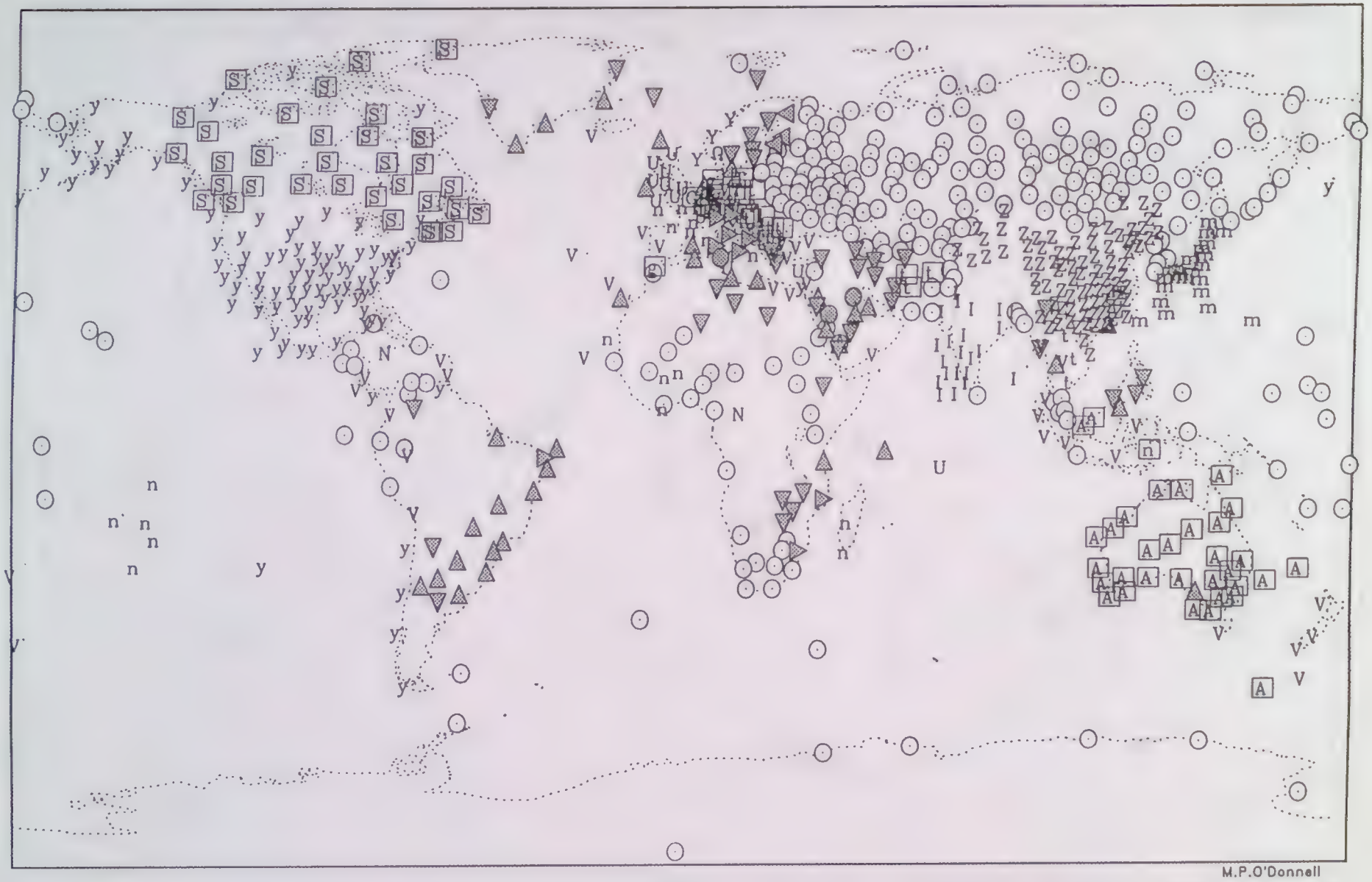
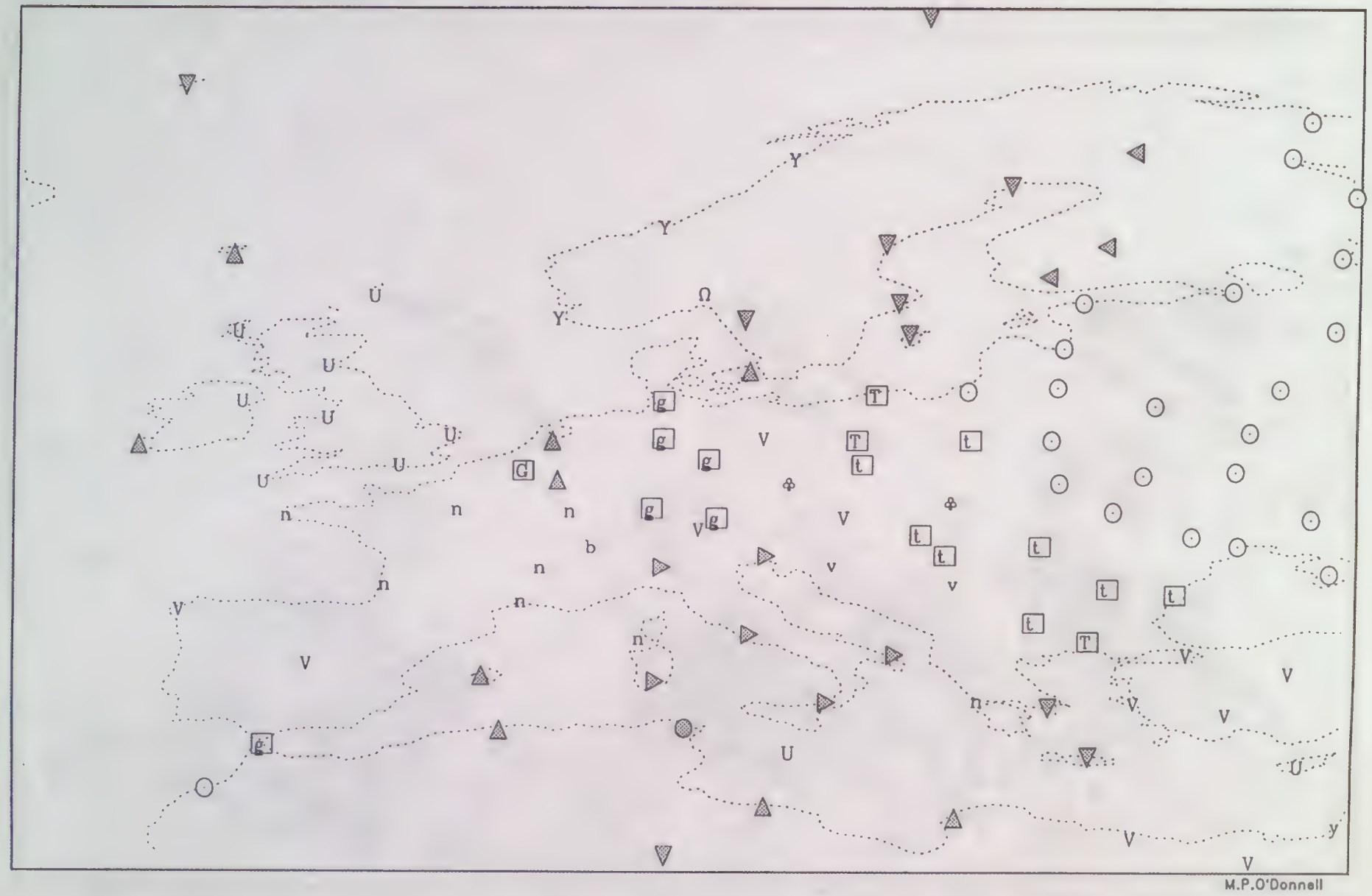


Figure 13c. Radiosonde instrumentation in use worldwide, 1982. From Parker and Cox (1994). Key follows Figure 13f.



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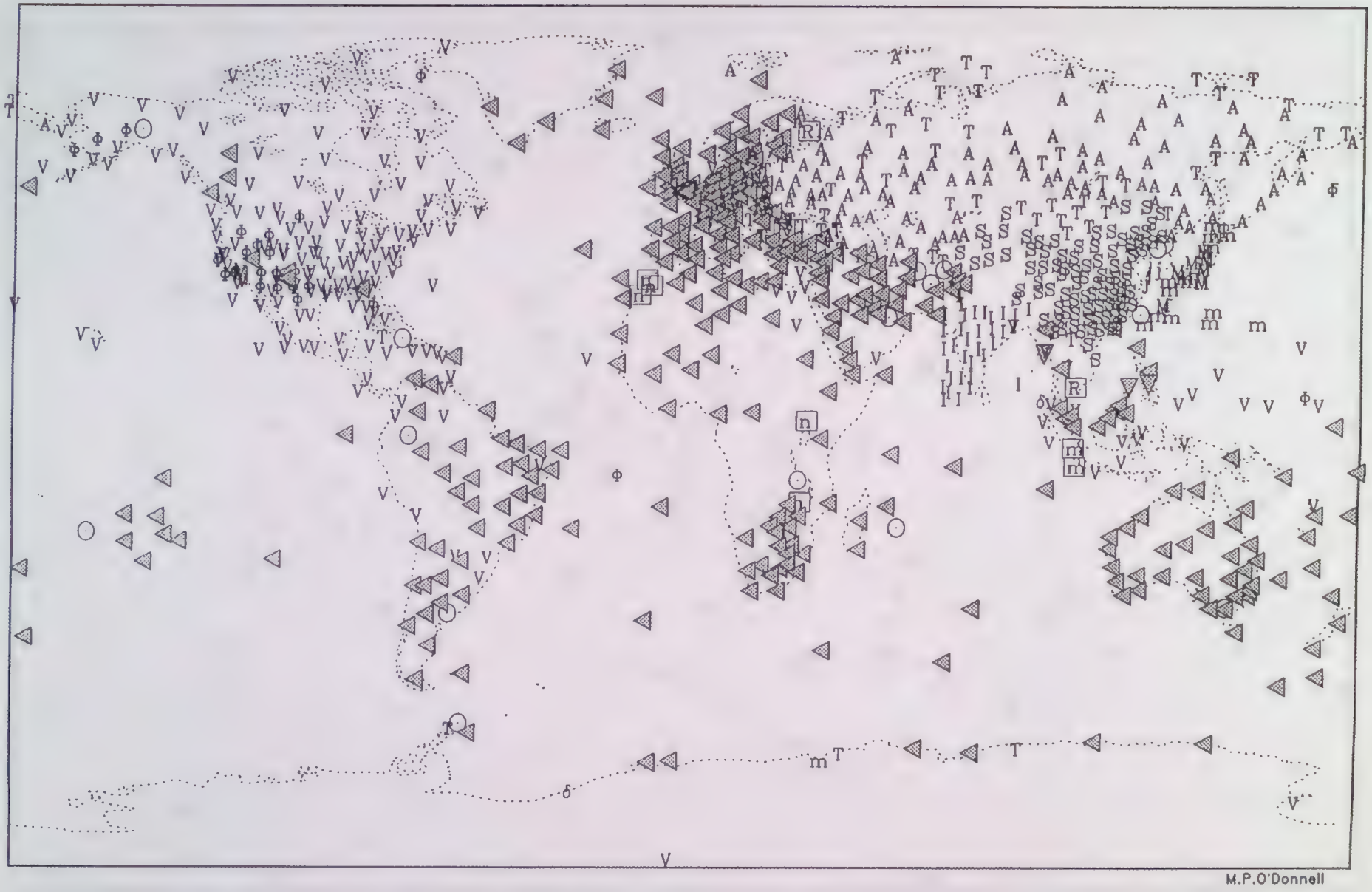

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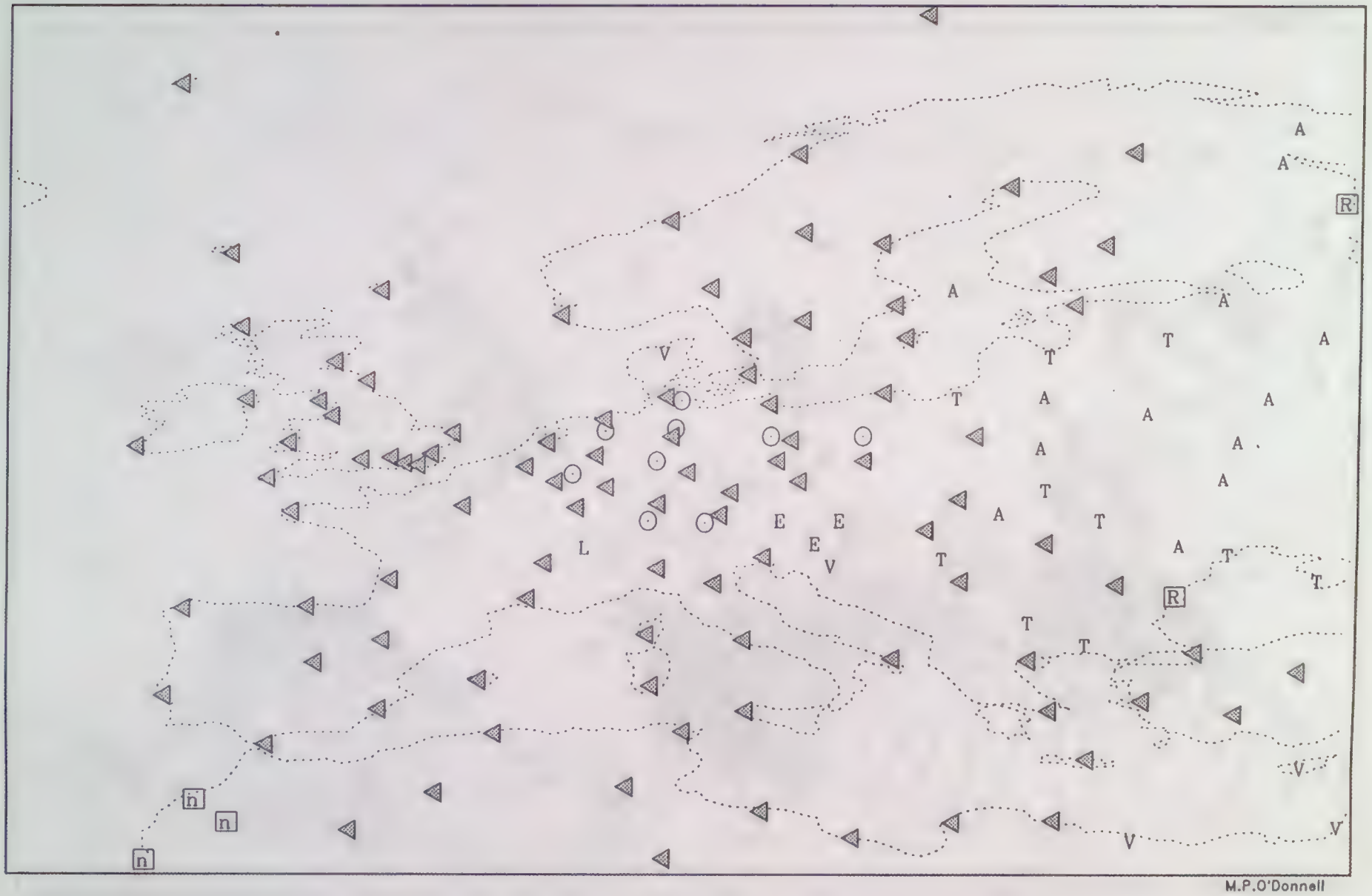
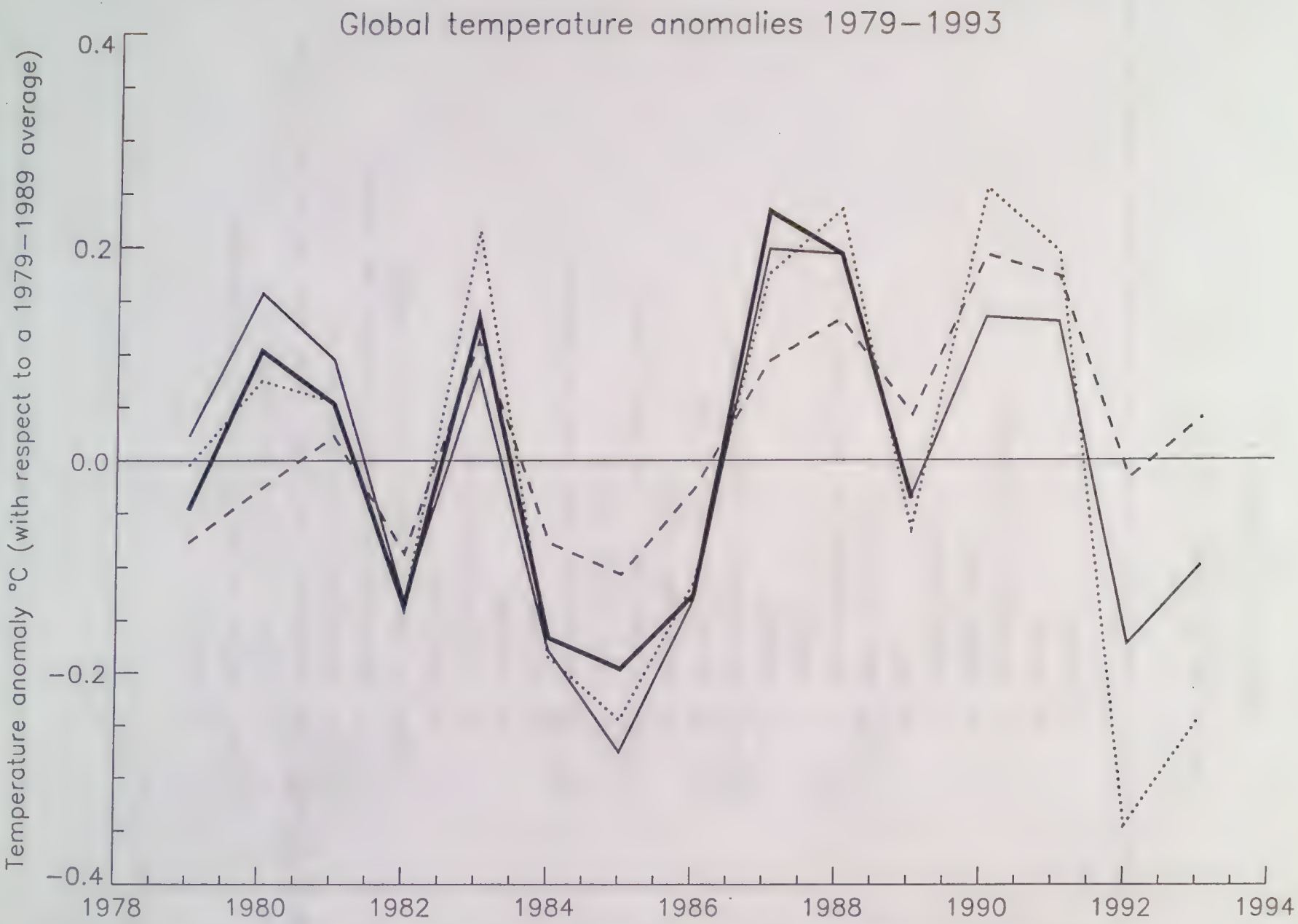


Figure 13f. As Figure 13e but for Europe. From Parker and Cox (1994). Key follows.

Key to Figure 13

[Similar types are listed on the same line]

A	AVK MRZ
B	BENDIX
c , C	CANADIAN MSC, CHRONOMETRIC
Z	CHINESE GZZ59
◇	DIAMOND HINMAN
E	ELIN
G , g , [G] , [g]	GRAW, H50, H60, M60
[i] , i , I	INDIAN CHRONOMETRIC, FAN, A SONDE MK 3
J	JAPANESE
j	JINGJANG
[m] m, M	MEISEI SONDE, RS 2 80, RS 2 91
N , n , [n]	MESURAL, FMO 1950A, MH 73A
L , b	METEOLABOR, BASORA
T , t , [T] , [t]	METEORIT SONDE, A 221V, RKZ-2, RKZ-5
X , x	METOX SONDE, METOX CT
[A] , a , [a]	PHILLIPS ASTOR RS-4, ASTOR 72, ASTOR 403
[S]	SANGAMO
S	SHANGHAI
Φ	SPACE DATA CORPORATION
♡	SWISS TYPE
U , k , [k] , W	UK SONDE, KEW MK 2, KEW MK 2B, WHITELEY
α , β , γ , δ	USA SONDE, CMD 18, USWB ELECTRONIC, INTELLISONDE
R , [r] , [R] , r	USSR SONDE, P3-049, A-22, RZ-049
●, ▽, △, ▷, ▩, ◁, ◆	VAISALA SONDE, RS 18, RS 21-12C, RS 21-13C, RS 38, RS 80, RS 12
Φ	VINOHRADY ZAP MARS 4WF BERLIN
V , v , Y , Ω , y	VIZ, AN/AMT, LORAN-C, OMEGA, J008 SOLID STATE
⊙	UNKNOWN



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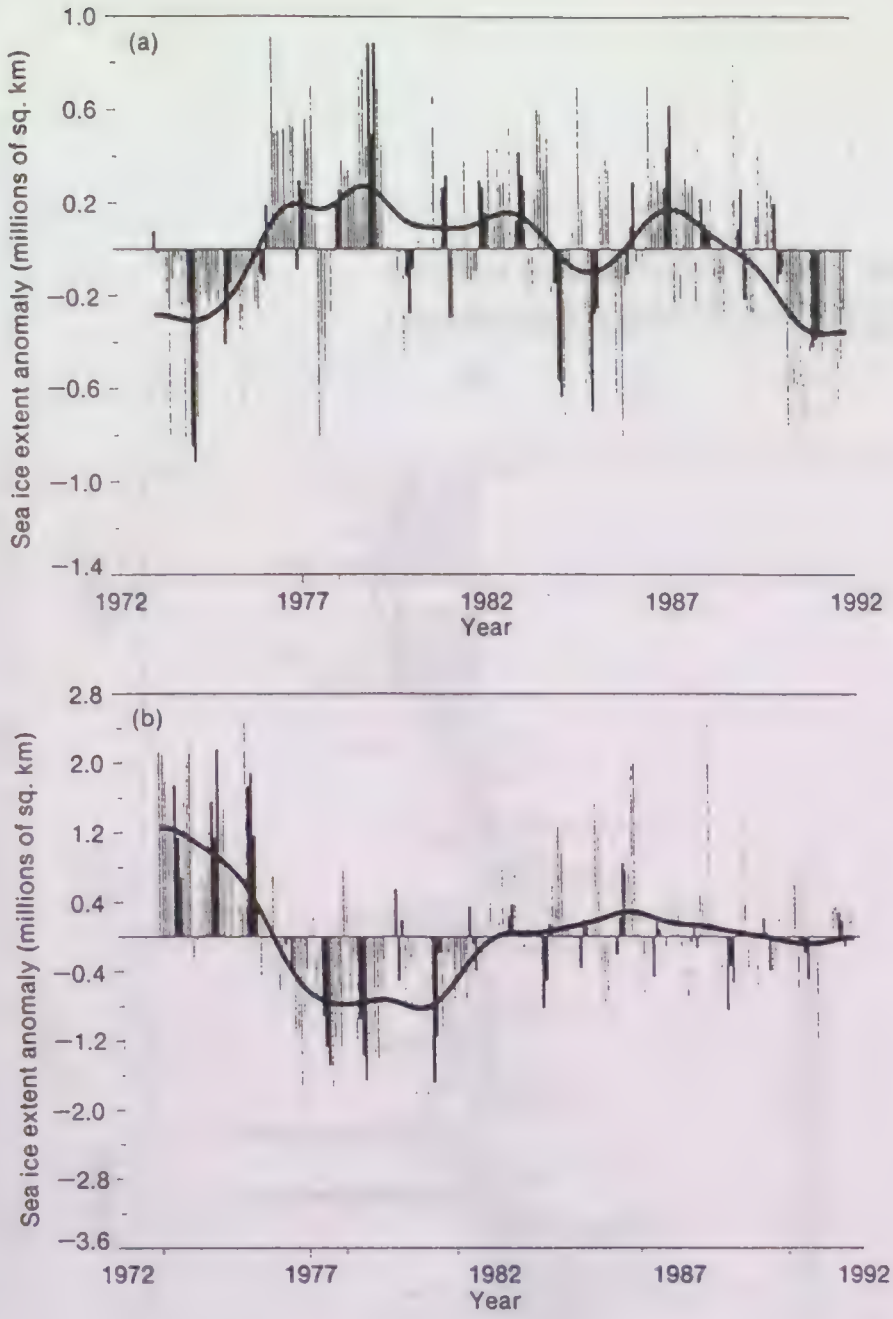

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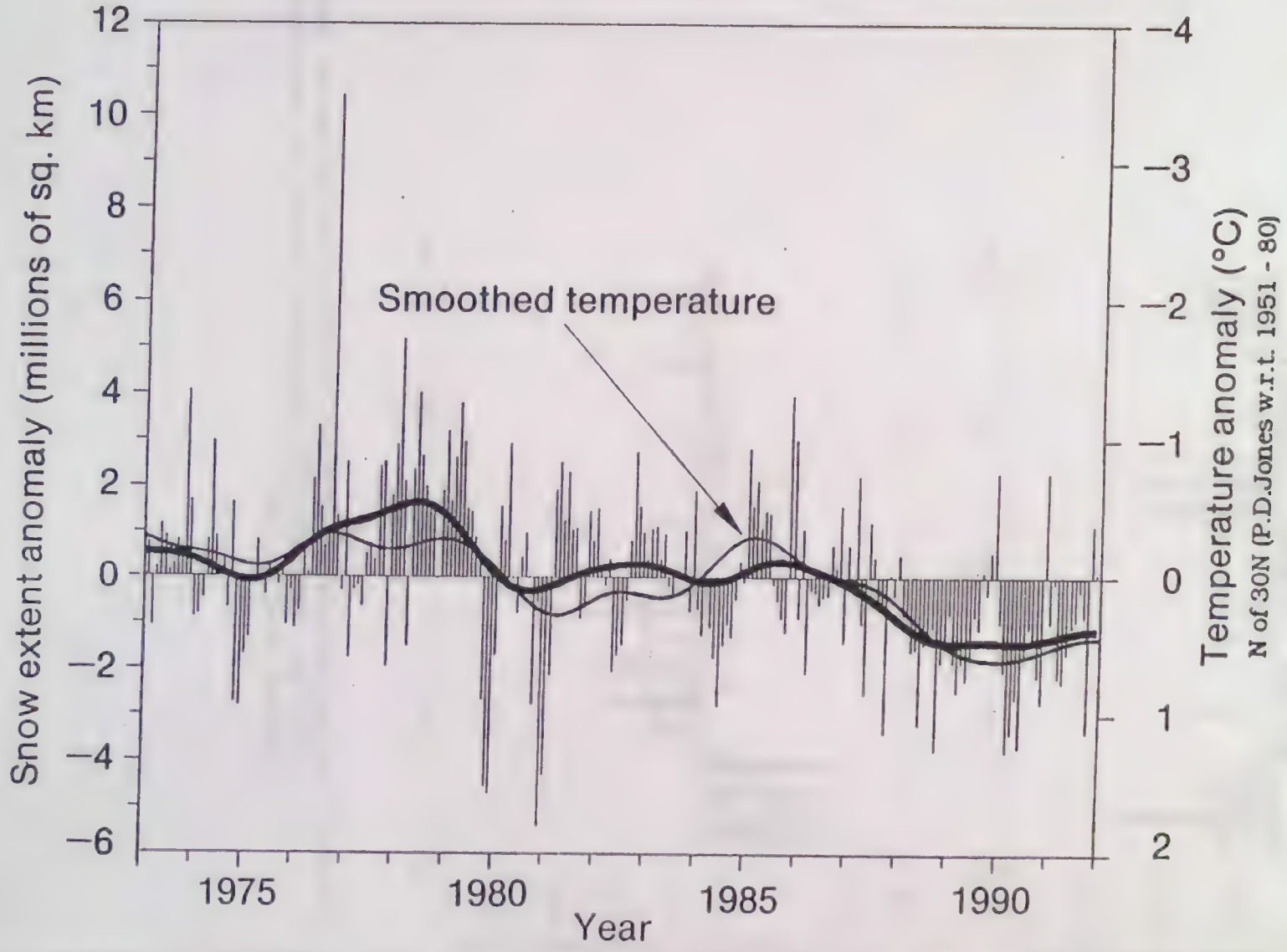
Northern Hemisphere Snow Cover Variations



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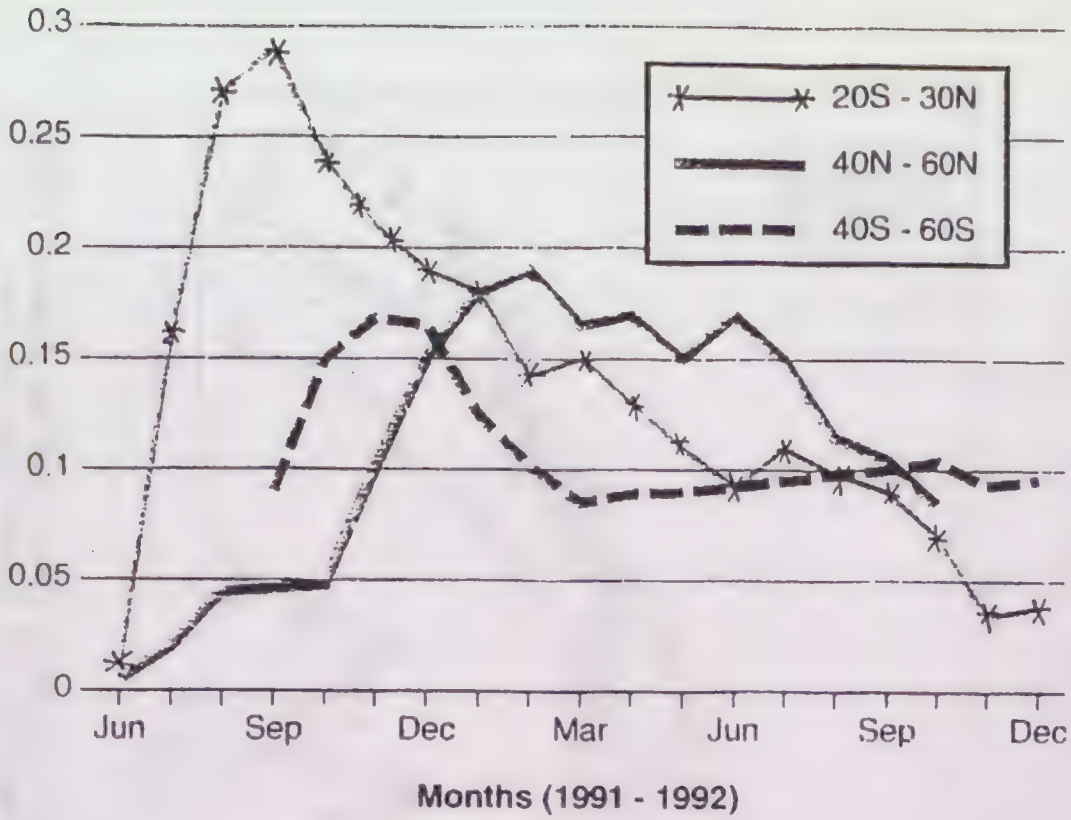

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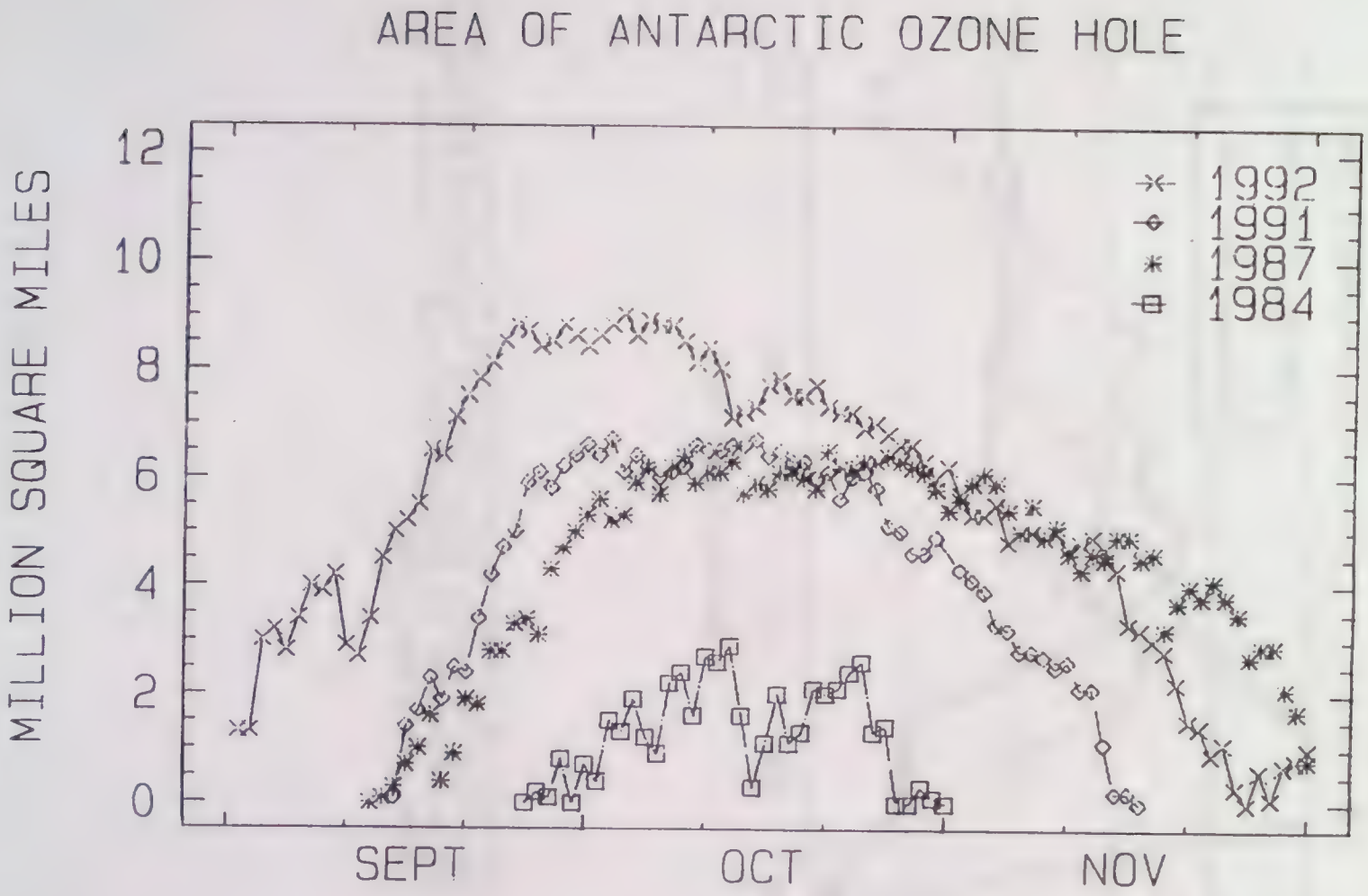

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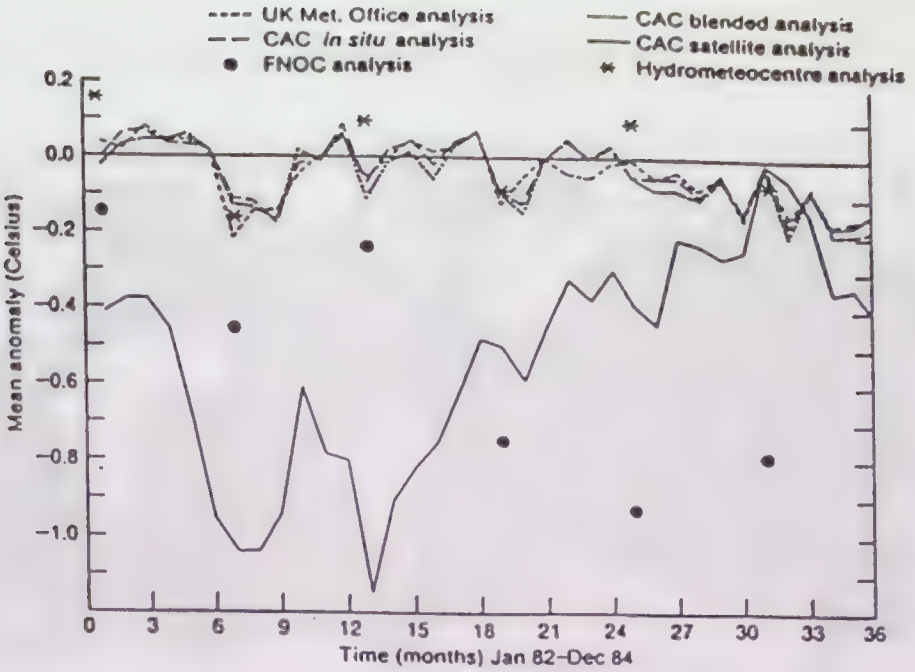

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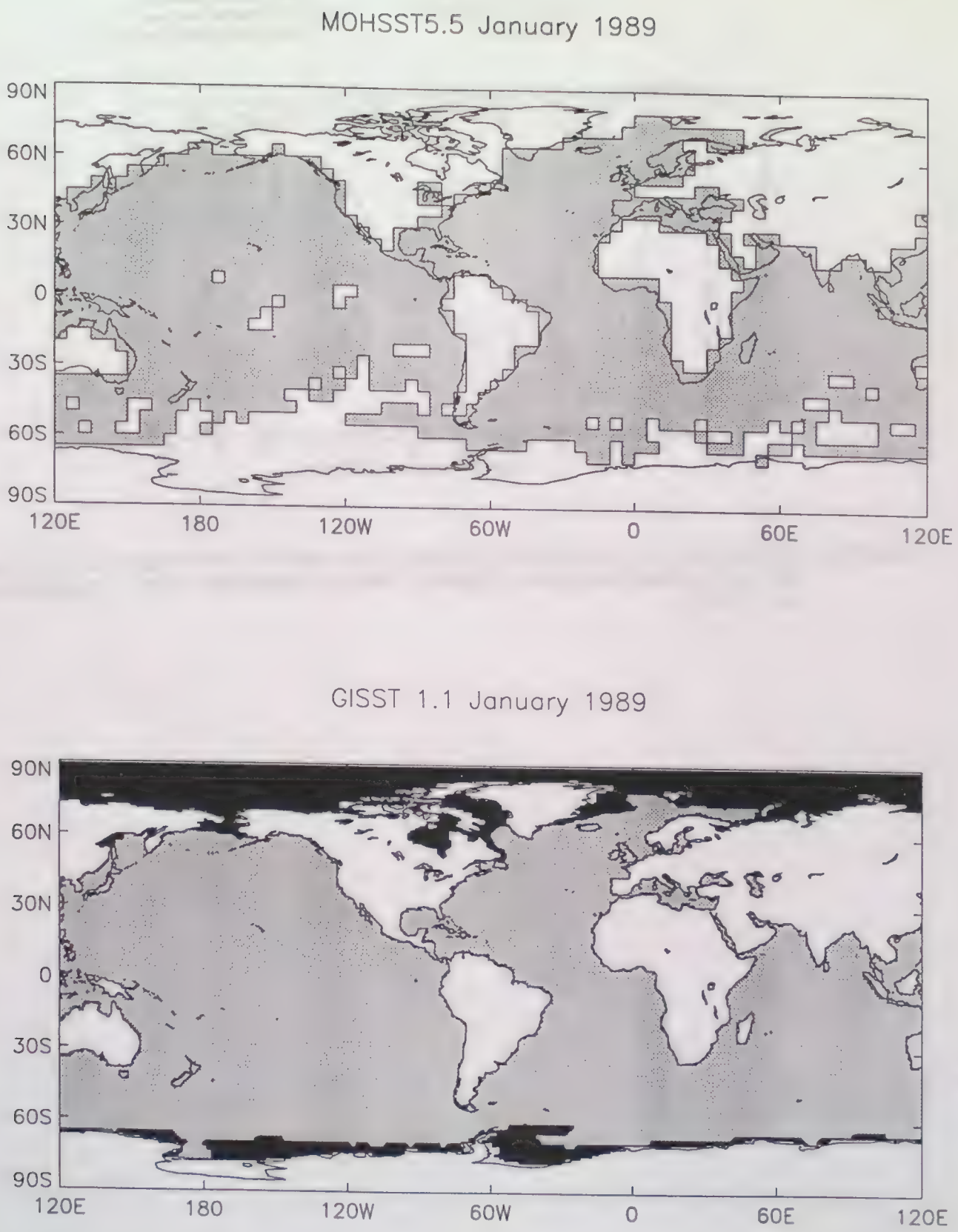

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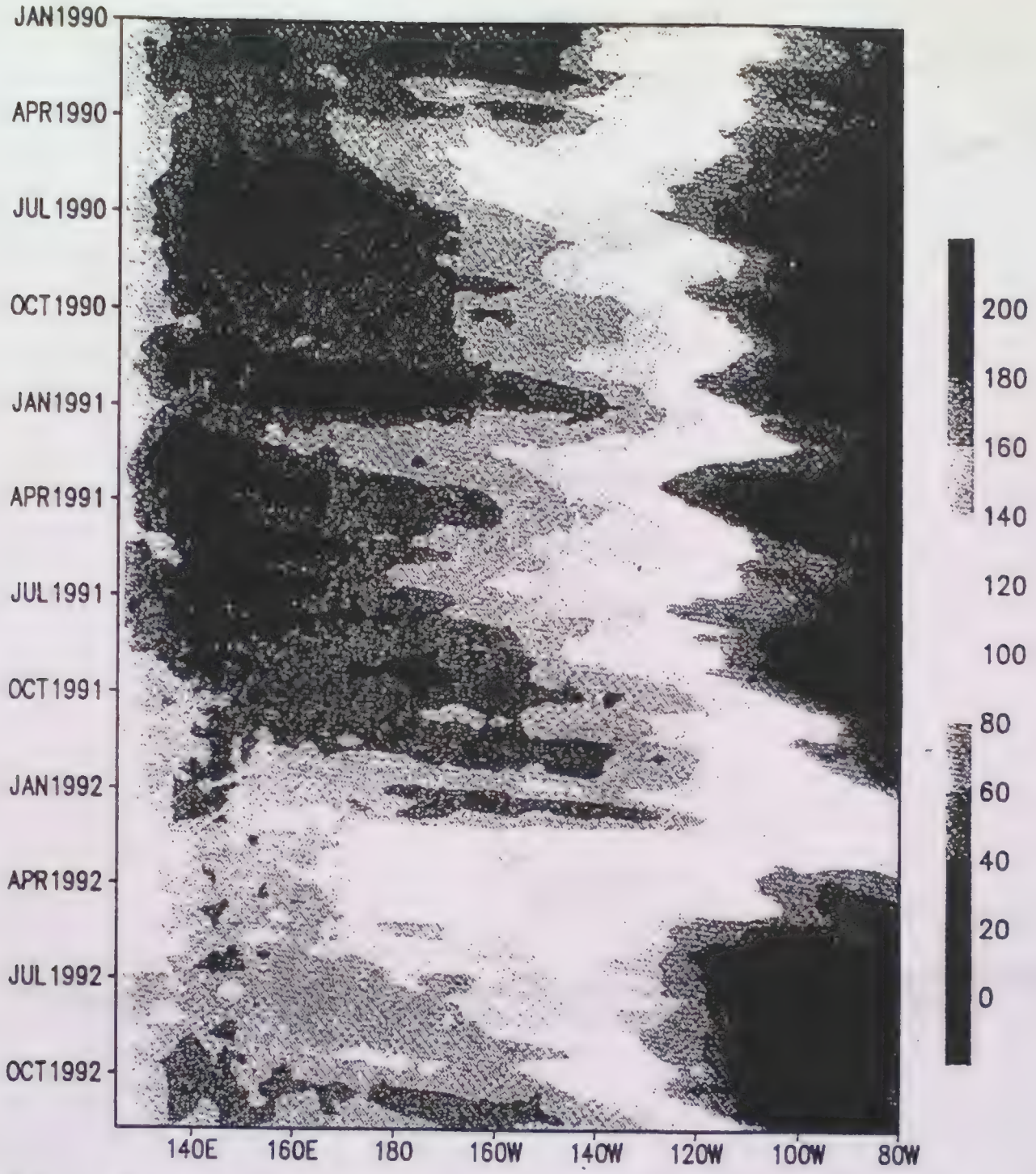

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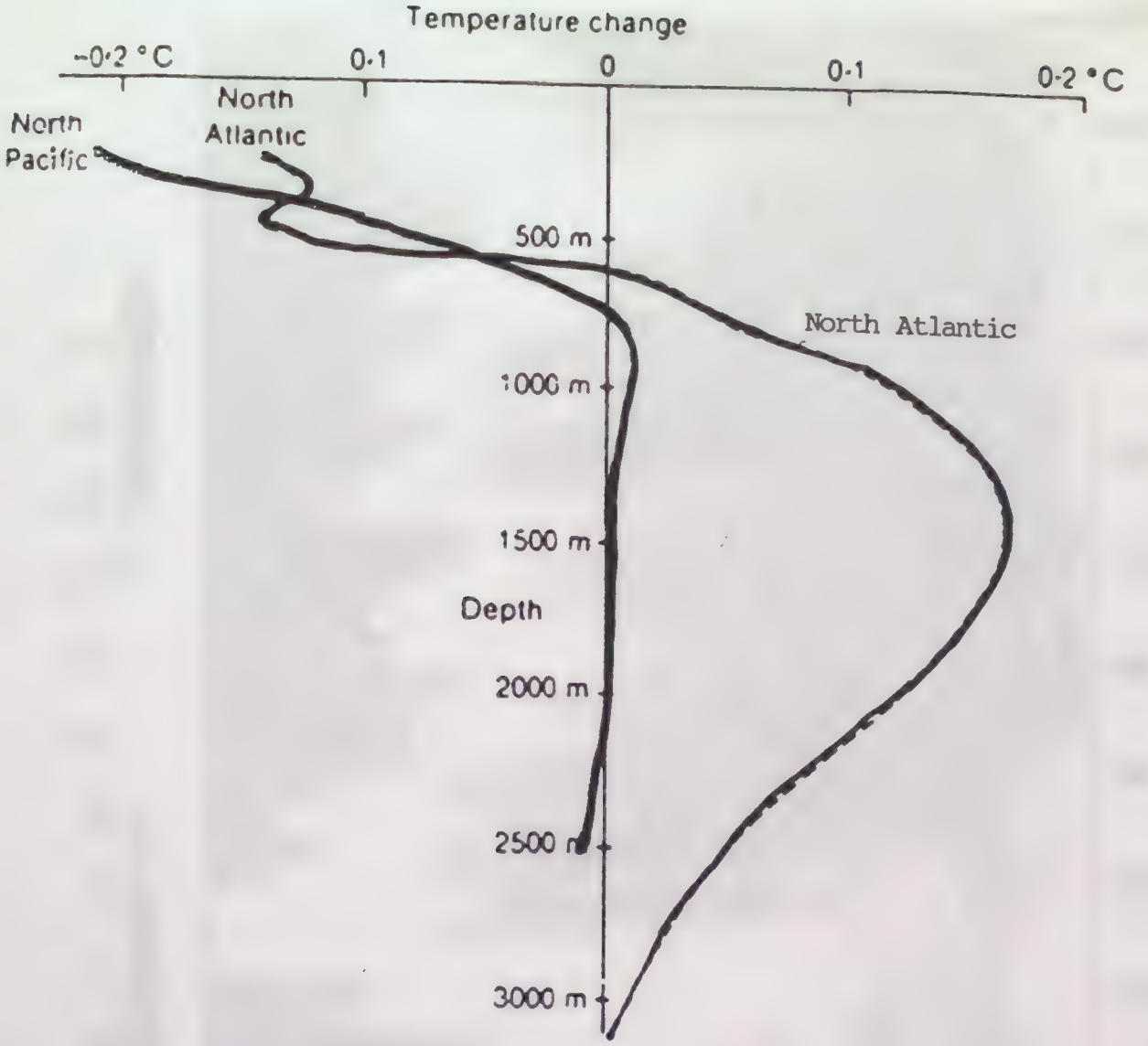

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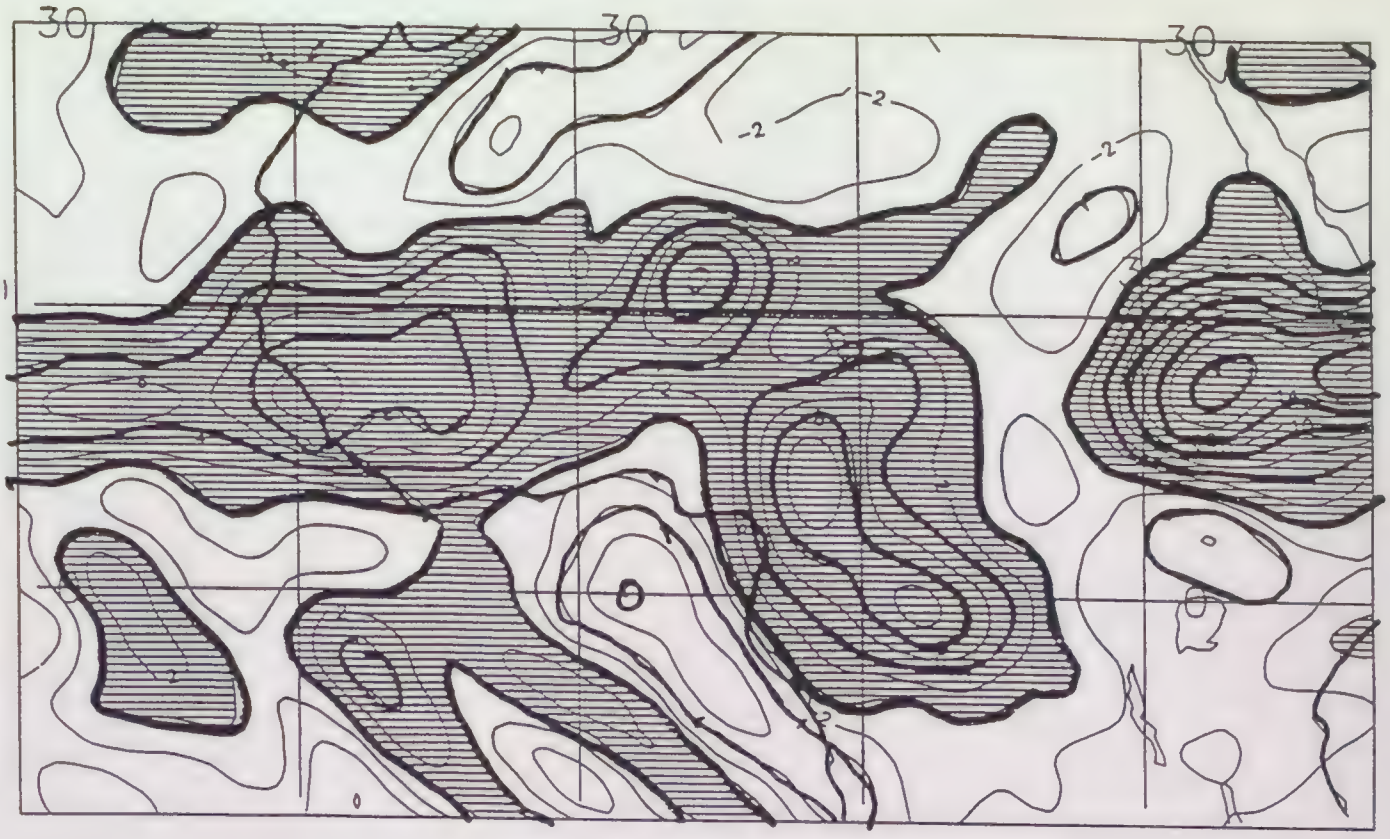
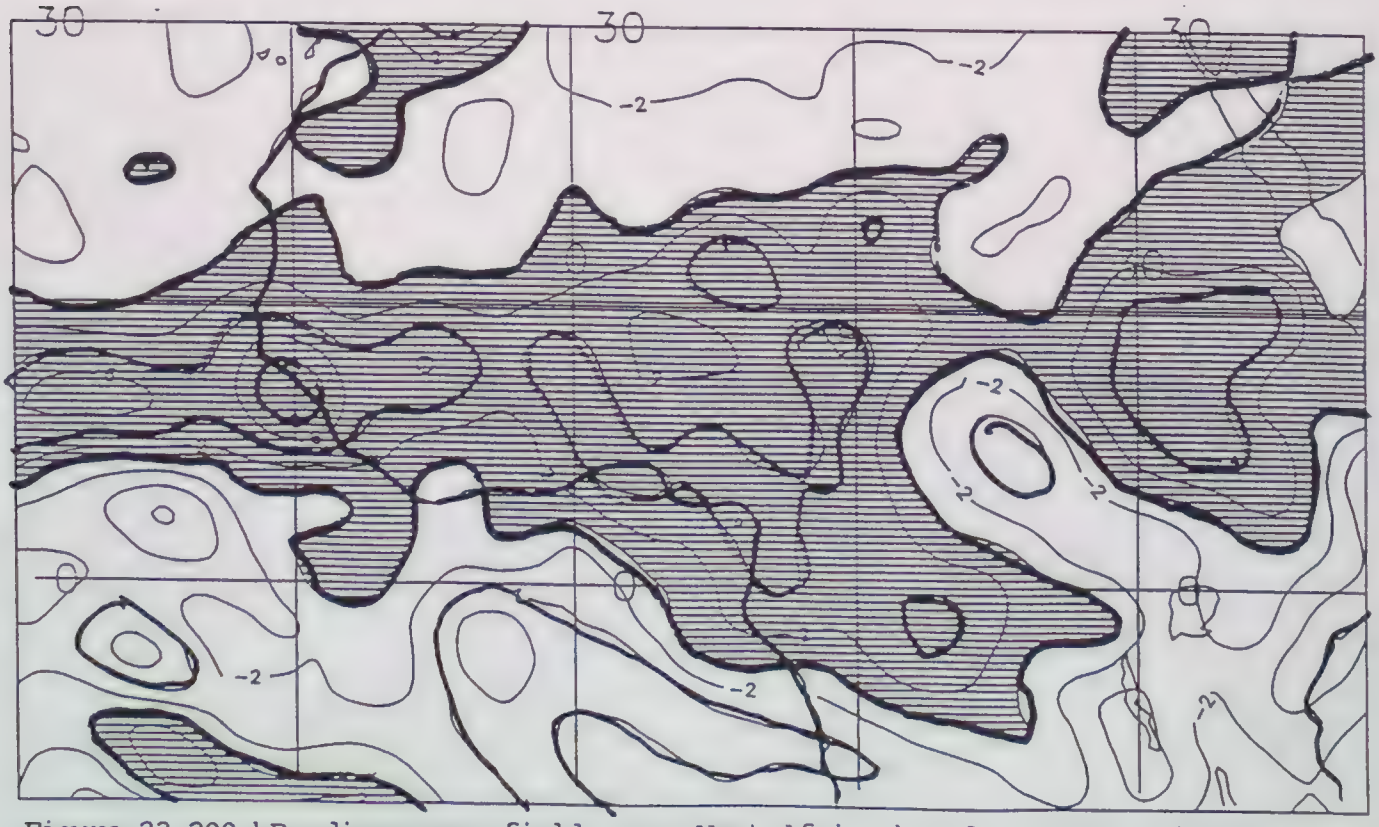


August 1991 (Sahel very dry)



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CRTN 2	Oct 1990	An ocean general circulation model of the Indian Ocean for hindcasting studies. D J Carrington
CRTN 3	Oct 1990	Simulation of the tropical diurnal cycle in a climate model. D P Rowell
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CRTN 5	Dec 1990	A comparison of 11-level General Circulation Model Simulations with observations in the East Sahel. K Maskell
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CRTN 8	Jan 1991	The role of observations in climate prediction and research. D J Carson
CRTN 9	Mar 1991	The greenhouse effect and its likely consequences for climate change. D J Carson
CRTN 10	Apr 1991	Use of wind stresses from operational N.W.P. models to force an O.G.C.M. of the Indian Ocean. D J Carrington
CRTN 11	Jun 1991	A new daily Central England Temperature series, 1772-1991. D E Parker, T P Legg and C K Folland
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CRTN 14	Sep 1991	Sea temperature bucket models used to correct historical SST data in the Meteorological Office. C K Folland
CRTN 15	Aug 1991	Modelling climate change, and some potential effects on agriculture in the U.K. P R Rowntree, B A Callander and J Cochrane
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CRTN 23	Feb 1992	The temporal evolution of Equatorial Currents in the Indian Ocean D L T Anderson, D J Carrington, R A Corry and C Gordon
CRTN 24	Feb 1992	Stratospheric analyses provided by the U.K. Meteorological Office M J Bailey, A O'Neill and V D Pope

CLIMATE RESEARCH TECHNICAL NOTES

CRTN 25	Feb 1992	Modelling interannual variability in the Indian Ocean using momentum fluxes from the UKMO and ECMWF operational weather analyses. D L T Anderson and D J Carrington
CRTN 26	Mar 1992	A GCM simulation of the impact of Amazonian deforestation on climate using an improved canopy representation J Lean and P R Rowntree
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